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MICHIGAN/AIR FORCE RESEARCH LABORATORY (AFRL) COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

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14. ABSTRACT
The mission of the Michigan/AFRL Collaborative Center in Control Science (MACCCS) was to establish, sustain and amplify an internationally recognized center of excellence in control science research and education, through interaction between the faculty and students at the participating universities, and AFRL. Concentration areas were: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV): i) design, modeling, analysis and control of flapping wing vehicles for collaborative UAV missions; ii) supervision and control of cooperative heterogeneous systems; iii) distributed, dynamic, sequential, combinatorial and/or stochastic mission planning; and iv) path planning and flight control to achieve autonomy in contested environments. 2. Air-Breathing Hypersonic Vehicles (ABHV): i) development of simple low-order models that characterize the main aerothermoelastic effects coupled with propulsion; ii) vehicle configuration to improve dynamic controllability without compromising performance; iii) operability limits, controllability and uncertainty input to an adaptive control model of hypersonic vehicles; and iv) adaptive control of hypersonic vehicles.

15. SUBJECT TERMS
control systems, cooperative control, unmanned air vehicles (UAV), flapping-wing vehicles, air-breathing hypersonic vehicles (ABHV)

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1. Summary

The mission of the Michigan/AFRL Collaborative Center in Control Science (MACCCS) was to establish, sustain and amplify an internationally recognized center of excellence in control science research and education, through interaction between the faculty and students at the participating universities, and AFRL. Concentration areas were: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV): i) design, modeling, analysis and control of flapping wing vehicles for collaborative UAV missions; ii) supervision and control of cooperative heterogeneous systems; iii) distributed, dynamic, sequential, combinatorial and/or stochastic mission planning; and (iv) path planning and flight control to achieve autonomy in contested environments. 2. Air-Breathing Hypersonic Vehicles (ABHV): i) development of simple low-order models that characterize the main aerothermoelastic effects coupled with propulsion; ii) vehicle configuration to improve dynamic controllability without compromising performance; iii) operability limits, controllability and uncertainty input to an adaptive control model of hypersonic vehicles; and iv) adaptive control of hypersonic vehicles.

MACCCS lasted from 2007 to 2016. It included, on the Universities' side, 10 participating faculty, 9 visiting faculty or post-doctoral researchers, 29 PhD students, and 16 Master's students, as well as numerous researchers from AFRL. Notable publications included 1 textbook, 57 archival journal papers, and 135 conference papers. Eleven major model or algorithm releases were accomplished. Details are provided below. Research summaries for all years are included as an appendix.

2. People

2.1 Participating Faculty (10)

University of Michigan:
Anouck Girard, PI, 2007-2016
Carlos Cesnik, Co-PI, 2007-2011
James Driscoll, 2007-2016
Pierre Kabamba, 2011-2014
Nadine Sarter, 2008-2011

Massachusetts Institute of Technology:
Anuradha Annaswamy, 2011-2016
Missy Cummings, 2009-2011
Emilio Frazzoli, 2007-2016

Ohio State University:
Andrea Serrani, 2007-2008

Purdue University:
XinYan Deng, 2011-2016

2.2 Visiting Faculty and Post-Doctoral Researchers (9)

Visiting Faculty (4)
Tal Shima, Technion, 2008, 2009, 2010, 2012
Emanuele Garone, Universite Libre de Bruxelles, 2015
Yildiray Yildiz, Bilkent University, 2015
Jason Speyer, UCLA, 2016

Post-Doctoral Researchers (5)
Weilin Wang, UM, 2008-2011
Baro Hyun, UM 2011-2012
Ricardo Bencatel, 2013-2015
Luca Bertucelli, MIT, 2010-2012
Ketan Savla, MIT, 2010-2011

2.3 Ph.D. Students (29)

Cesnik (2)
N. Falkiewicz, 2011
T. Skujins, 2012

Driscoll (4)
S. Torrez, 2012
D. Dalle, 2013
M. Fotia, 2012
C. Marley, 2017 (expected)

Girard/Kabamba (9)
A. Klesh. 2009 (NDSEG, MAX topic)
C. Orlowski, 2011 (US Army, MAX topic)
B. Hyun, 2011
J. Jackson, 2012
J. Richardson, 2012 (NDSEG, MAX topic)
J. Las Fargeas, 2015
D. Oyler, 2016
M. Niendorf, 2016
J. Seok, 2017 (expected)

Sarter (2)
T. Ferris, 2010
S. Jayaraman, 2010

Annaswamy (1)
Daniel Wiese, 2016

Frazzoli (8)
John Enright, 2009
Marco Pavone, 2010
Tom Temple, 2011
Sertac Karaman, 2012
Josh Bialkowski, 2013
Vu Huynh, 2014
Kyle Treleaven, 2014
Phil Root, 2014
Elaheh Fata, 2018 (expected)

Deng (2)
J. Roll, 2012
B. Cheng, 2012

Serrani (1)
Lisa Fiorentini, 2010

2.4 Master's Students (16)

Cesnik (1)
Ryan Klock, 2014

Driscoll (1)
Nate Scholten, 2008

Girard/Kabamba (11)
Shiyi Yang, Ballistic Drop Analysis in Wind, 2013.
David Cho, Pursuit Evasion Games for UAV and Ground Sensor Surveillance, 2013.
Yash Chitalia, Controller Design for FWMAV, 2013 (EECS).
Calvin Jee-Hun Park, Distributed Platforms for Task Assignment and Scheduling, 2012.
Zahid Hasan, Displacement Measurement Testbed for Flapping Wing MAV, 2011.
Clarence Hanson, Path Planning of a Dubins Vehicle for Sequential Target Observations with Ranged Sensors, 2011.
Yu-Hsien (John) Chang, Estimation and Optimal Exploration Systems, 2010.
Jonathan White, Distributed Software Architectures for Autonomous Systems, 2008.
John Baker, Human-Operator Modeling for Classification Tasks, 2007.
Amir Matlock, Heterogeneous Teams for Search, 2007.
Dongkyoung Lee, Autonomous Miniature Helicopter Hovering, 2007.

Cummings (1)
A. Caves, 2010.

Frazzoli (2)
Christine Siew, 2010
Luis Reyes Castro, 2014

3. Publications
3.1 Textbooks (1)

1. P. Kabamba and A. Girard. Fundamentals of Aerospace Navigation and Guidance. Cambridge University Press. 2014.

3.2 Journal Papers (57)

Cesnik (7)

1. Falkiewicz, N.J., Cesnik, C.E.S., Crowell, A.R., and McNamara, J.J., "Reduced-Order Aerothermoelastic Framework for Hypersonic Vehicle Control Simulation," *AIAA Journal*, Vol. 49, No. 8, August 2011.
2. Falkiewicz, N.J., and Cesnik, C.E.S., "Proper Orthogonal Decomposition for Reduced-Order Thermal Solution in Hypersonic Aerothermoelastic Simulations," AIAA Journal, Vol. 49, No. 5, May 2011.
3. Skujins, T., Cesnik, C.E.S., Oppenheimer, M.W., and Doman, D.B., "Canard-Elevon Interactions on a Hypersonic Vehicle," *Journal of Spacecraft and Rockets*, Vol. 47, No. 1, January-February 2010, pp. 90-100.
4. Falkiewicz, N.J. and Cesnik, C.E.S., "A Partitioned Solution Framework for Time-Domain Aerothermoelastic Simulation of Hypersonic Vehicles," AIAA Journal, final review process.
5. Falkiewicz, N.J. and Cesnik, C.E.S., "Enhanced Modal Solutions for Structural Dynamics in Aerothermoelastic Analysis," AIAA Journal, final review process.
6. Skujins, T. and Cesnik, C.E.S., "Reduced-Order Modeling of Unsteady Aerodynamics Across Multiple Mach Regimes," Journal of Aircraft, final review process.
7. Skujins, T. and Cesnik, C.E.S., "Reduced-Order Modeling of High-Speed Unsteady Aerodynamics," AIAA Journal, final review process.

Driscoll (9)

1. Dalle, D.J, Fotia, M.L., Driscoll, J.F., Reduced-Order Modeling of Two-Dimensional Supersonic Flows with Applications to Scramjet Inlets, J. of Propulsion and Power, 26,3, 545-555, 2010.
2. Torrez, S.M., Driscoll, J.F., Ihme, M., Fotia, M.L., Reduced Order Modeling of Turbulent Reacting Flows With Application to Ramjets and Scramjets, J. of Propulsion and Power, 27, 2, 371-382, 2011.
3. Fotia, M.L. and Driscoll, J.F., Isolator-Combustor Interactions in a Direct-Connect Ramjet-Scramjet Experiment, J. Propulsion and Power 28, 1, 83-85, 2012.
4. Dalle, D.J., Torrez, S.M. and Driscoll, J.F., Rapid Analysis of Scramjet and Linear Plug Nozzles, J. Propulsion and Power 28, 3, 545-555, 2012.
5. Fotia, M.L., Driscoll, J.F., Ram-Scram Transition and Flame/Shock-Train Interactions in a Model Scramjet Experiment, J. Propulsion and Power, 29, 1, 261-273, 2012.
6. Torrez, S.M., Dalle, D.J. and Driscoll, J.F., A New Method for Computing Performance of Choked Reacting Flows and Ram-to-Scram Transition, J. Propulsion and Power 29, 2, 433-445, 2013.
7. Dalle, D. J., Torrez, S.M., Driscoll, J.F., Bolender, M.A., Bowcutt, K.G., Minimum-Fuel Ascent of a Hypersonic Vehicle Using Surrogate Optimization, AIAA J. of Aircraft 51, 6 (2014) 1973-1986.
8. Dalle, D.J., Driscoll, J.F., Torrez, S.M., Ascent Trajectories of Hypersonic Aircraft:

Operability Limits Due to Engine Unstart, Journal of Aircraft: 52, 4, 1345-1354, 2015. 10.2514 / 1.C032801
9. Lamorte, N., Friedmann, P.P., Dalle, D. J., Torrez, S.M., Driscoll, J.F., Uncertainty Propagation in Integrated Airframe-Propulsion System Analysis for Hypersonic Vehicles, J. of Propulsion and Power, 31, 1 (2015) 54-68.

Girard/Kabamba (27)

1. M. Niendorf, P. Kabamba, and A. Girard. Stability Analysis of Runway Schedules. IEEE Transactions on Intelligent Transportation Systems. Accepted for Publication, March 2016.
2. J. Seok, J. Kasa-Vubu, M. DiPietro and A. Girard. Expert System for Automated Bone Age Determination. Expert Systems with Applications. Vol. 50, pp. 7588, 15 May 2016.
3. J. Las Fargeas, M. Niendorf, P. Kabamba, and A. Girard. Stability and Criticality Analysis for Integer Linear Programs with Markovian Problem Data. IEEE Transactions on Automatic Control. Vol. 61, No. 6, June 2016, pp. 1466-76.
4. M. Niendorf, P. Kabamba and A. Girard. Stability of Solutions to Classes of the Traveling Salesman Problem. IEEE Transactions on Cybernetics, Vol. 46, No. 4, pp 973-985, April 2016.
5. D. Oyler, P. Kabamba and A. Girard. Pursuit-Evasion Games in the Presence of Obstacles. Automatica. Vol. 65, March 2016, pp. 1-11.
6. A. Girard and P. Kabamba. Proportional Navigation: Optimal Homing and Optimal Evasion. SIAM Review Vol. 57, No. 4, pp. 611 - 624, November 2015.
7. J. Las Fargeas, P. Kabamba, and A. Girard. Optimal Configuration of Alarm Sensors for Monitoring Mobile Ergodic Markov Phenomena on Arbitrary Graphs. IEEE Sensors Journal. Vol.15, No.6, pp. 3622 - 3634, June 2015.
8. D. Oyler, P. Kabamba, and A. Girard. Binary Range-Rate Measurements and Homing Guidance. ASME Journal of Dynamic Systems, Measurement and Control. Vol. 137, No. 4, pp. 041010-041010-12, April 2015.
9. J. Las Fargeas, P. Kabamba, and A. Girard. Cooperative Surveillance and Pursuit using Unmanned Aerial Vehicles and Unattended Ground Sensors. Sensors, Special Issue on UAV Sensors for Environmental Monitoring, Vol. 15, No. 1, pp. 1365-1388, January 2015.
10. B. Hyun, P. Kabamba, and A. Girard. Optimal Classi_cation by Mixed-Initiative Nested Thresholding. IEEE Transactions on Cybernetics. Vol. 45, No. 1, pp. 29-39, January 2015.
11. J. Richardson, E. Atkins, P. Kabamba and A. Girard. Safety Margins for Flight Through Stochastic Gusts. AIAA Journal of Guidance, Control and Dynamics. Vol. 37, No. 6, pp. 2026-2030, October 2014.
12. J. Richardson, E. Atkins, P. Kabamba and A. Girard. Scaling of Airplane Dynamic Response to Stochastic Gusts. AIAA Journal. AIAA Journal, (2014), Vol. 51, No. 5, pp. 1554-1566, September 2014.
13. R. Bencatel, P. Kabamba, and A. Girard. Perpetual Dynamic Soaring in Linear Wind Shear. AIAA Journal of Guidance, Control and Dynamics. Vol. 37, No. 5, pp. 1712-1716, September 2014.
14. B. Hyun, W. Zhang, P. Kabamba, and A. Girard. Informative Path Planning for Improving Classification Performance through Kinematic Decisions. Unmanned Systems. Vol. 2 No. 2, pp. 143-156, April 2014.
15. M. Faied and A. Girard. Game Formulation of Multi-Team Target Assignment and Suppression Mission. IEEE Transactions on Aerospace and Electronic Systems. Vol. 50, No. 2, pp.1234-1248, January 2014.
16. B. Hyun, P. Kabamba, and A. Girard. Strategic Path Planning by Sequential Parametric

Bayesian Decisions. International Journal of Advanced Robotic Systems. Vol. 10, No. 390, November 2013.
17. J. Richardson, E. Atkins, P. Kabamba and A. Girard. Envelopes for Flight Through Stochastic Gusts. AIAA Journal of Guidance, Control and Dynamics. Vol. 36, No. 5, pp. 1464-1476, September 2013.
18. R. Bencatel, J. Tasso Sousa and A. Girard. Atmospheric Flow Field Models Applicable for Aircraft Endurance Extension. Progress in Aerospace Sciences. Vol. 61, pp. 1-25, August 2013.
19. J. Jackson, M. Faied, P. Kabamba and A. Girard. Distributed Constrained Minimum-Time Schedules in Networks of Arbitrary Topology. IEEE Transactions on Robotics. Vol. 29, No. 2, pp. 554-563, April 2013.
20. C. Orlowski and A. Girard. Longitudinal Flight Dynamics of Flapping-Wing Micro Air Vehicles. AIAA Journal of Guidance, Control and Dynamics, Vol. 35, No. 4, pp. 1115-1131, July-August 2012.
21. C. Orlowski and A. Girard. Dynamics, Stability, and Control Analyses of Flapping Wing Micro Air Vehicles. Progress in Aerospace Sciences, Vol. 51, pp. 1830, May 2012.
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23. J. Jackson, M. Faied, A. Girard. Comparison of Tabu/2-opt Heuristic and Optimal Tree Search Method for Assignment Problems. International Journal of Robust and Nonlinear Control. Vol. 21, No. 12, pp. 1355-1492, August 2011.
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25. W. Wang, A. R. Girard, S. Lafortune, and F. Lin. On Codiagnosability and Coobservability with Dynamic Observations. IEEE Transactions on Automatic Control. Vol. 56, No. 7, pp. 1551 - 1566, July 2011.
26. W. Wang, S. Lafortune, F. Lin, and A. R. Girard. Minimization of Dynamic Sensor Activation in Discrete Event Systems for the Purpose of Control. IEEE Transactions on Automatic Control. Vol. 55, No. 11, pp. 2447-2461, Nov. 2010.
27. W. Wang, S. Lafortune, A. R. Girard, and F. Lin. Optimal Dynamic Sensor Activation for Diagnosing Discrete Event Systems. Automatica. Vol. 46, No. 7, pp. 1165-1175, July 2010.

Sarter (1)

1. Ferris, T. and Sarter, N. (2008). Crossmodal links among vision, audition, and touch in complex environments. Human Factors, 50 (1), 17-26.

Annaswamy: (2)

1. D. Wiese, A.M. Annaswamy, J.A. Muse, M.A. Bolender. Adaptive Output Feedback Based on Closed-Loop Reference Models for Hypersonic Vehicles. AIAA Journal of Guidance, Control, and Dynamics. 38.12 (2015): 2429-2440.
2. D. Wiese, A.M. Annaswamy, J.A. Muse, M.A. Bolender. Sequential Loop Closure Based Adaptive Output Feedback. IEEE Transactions on Control Systems Technology. (To be submitted, 2016)

Frazzoli (10)

1. J. Bialkowski, M. Otte, S. Karaman, and E. Frazzoli. Efficient collision checking in sampling-based motion planning via safety certificates. Int. Journal of Robotics Research, 35(7):767–796, 2016.

2. V. A. Huynh, S. Karaman, and E. Frazzoli. An incremental sampling-based algorithm for stochastic optimal control. Int. Journal of Robotics Research, 2016. To appear.
3. M. Otte and E. Frazzoli. RRT-X: Asymptotically optimal single-query sampling-based motion planning with quick replanning. Int. Journal of Robotics Research, 2015.
4. K. Savla and E. Frazzoli. A dynamical queue approach to intelligent task management for human operators. Proceedings of the IEEE, 100(3), 2012.
5. S. Karaman, T. Shima, and E. Frazzoli. A process algebra genetic algorithm. IEEE Trans. Evolutionary Computation, 16(4):489–503, 2012.
6. S. Karaman and E. Frazzoli. Sampling-based algorithms for optimal motion planning. Int. Journal of Robotics Research, 30(7):846–894, June 2011.
7. F. Bullo, E. Frazzoli, M. Pavone, K. Savla, and S. Smith. Dynamic vehicle routing for robotic systems. Proceedings of the IEEE, 99(9):1482–1504, 2011.
8. K. Savla and E. Frazzoli. Maximally stabilizing task release control policy for a dynamical queue. IEEE Trans. Automatic Control, 55(11):2655–2660, 2010.
9. M. Pavone, K. Savla, and E. Frazzoli. Sharing the load. IEEE Robotics and Automation Magazine, 16(2):52–61, 2009.
10. J. J. Enright, K. Savla, E. Frazzoli, and F. Bullo. Stochastic and dynamic routing problems for multiple UAVs. AIAA J. of Guidance, Control, and Dynamics, 32(4):1152–1166, 2009.

Serrani (1)

1. Fiorentini,Lisa; Serrani,Andrea; Bolender,Michael,A; Doman,David,B, 2009, "Nonlinear Robust Adaptive Control of Flexible Air-Breathing Hypersonic Vehicles." Journal of Guidance, Control and Dynamics, vol. 32, no. 2, 402 - 417.

Deng (0)

3.3 Conference Papers (135)

Cesnik: (17)

1. Klock, R.J. and Cesnik, C.E.S., “Aerothermoelastic Simulation of Air-Breathing Hypersonic Vehicle,” AIAA Science and Technology Forum and Exposition (SciTech2014), National Harbor, Maryland, 13—17 January 2014.
2. Skujins, T. and Cesnik, C.E.S., “Toward an Unsteady Aerodynamic ROM for Multiple Mach Regimes,” Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, April 2012, AIAA 2012-1708
3. Falkiewicz, N.J., Frendreis, S.G.V., and Cesnik, C.E.S., “Effect of Control Surface-Fuselage Inertial Coupling on Hypersonic Vehicle Flight Dynamics,” Proceedings of the 2011 Atmospheric Flight Mechanics Conference, Portland, Oregon, August 2011, AIAA 2011-6378. **(Best AFM Student Paper Award)**
4. Skujins, T. and Cesnik, C.E.S., “On the Applicability of an Unsteady Aerodynamic ROM to the Transonic Regime,” Proceedings of the 2011 Atmospheric Flight Mechanics Conference, Portland, Oregon, August 2011, AIAA 2011-6525.
5. Falkiewicz, N.J., and Cesnik, C.E.S., “Enhanced Modal Solutions for Structural Dynamics in Aerothermoelastic Analysis,” Proceedings of the 13th AIAA Dynamic Specialist Conference, Denver, Colorado, April 2011, AIAA 2011-1963.
6. Skujins, T. and Cesnik, C.E.S., “Reduced-Order Modeling of Hypersonic Unsteady Aerodynamics Due to Multi-Modal Oscillations,” Proceedings of the 17th AIAA International

Space Planes and Hypersonic Systems and Technologies Conference, San Francisco, California, April 2011, AIAA-2011-2341 .

7. Dalle, D. J., Frendreis, S. G. V., Driscoll, J. F., and Cesnik, C. E. S., "Hypersonic Vehicle Flight Dynamics with Coupled Aerodynamics and Reduced-order Propulsive Models," AIAA Atmospheric Flight Mechanics Conference, Toronto, Ontario, Canada, August 2010, AIAA 2010-7930.
8. Falkiewicz, N.J., Cesnik, C.E.S., Crowell, A.R., and McNamara, J.J., "Reduced-Order Aerothermoelastic Framework for Hypersonic Vehicle Control Simulation," Proceedings of the 2010 AIAA Atmospheric Flight Mechanics Conference, Toronto, Ontario, Canada, August 2010, AIAA 2010-7928.
9. Frendreis, S. G. V. and Cesnik, C. E. S., "3D Simulation of Flexible Hypersonic Vehicles," AIAA Atmospheric Flight Mechanics Conference, Toronto, Ontario, Canada, August 2010, AIAA 2010-8229.
10. Skujins, T. and Cesnik, C.E.S., "Reduced-Order Modeling of Hypersonic Vehicle Unsteady Aerodynamics," Proceedings of the AIAA Guidance, Navigation, and Control Conference, August 2010, AIAA 2010-8127.
11. Falkiewicz, N.J., and Cesnik, C.E.S., "Proper Orthogonal Decomposition for Reduced-Order Thermal Solution in Hypersonic Aerothermoelastic Simulations," Proceedings of the 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Orlando, Florida, April 2010, AIAA 2010-2798.
12. Falkiewicz, N.J., Cesnik, C.E.S., Bolender, M.A., and Doman, D.B., "Thermoelastic Formulation of a Hypersonic Vehicle Control Surface for Control-Oriented Simulation," Proceedings of the 2009 Guidance, Navigation, and Control Conference and Exhibit, Chicago, Illinois, August 2009, AIAA 2009-6284.
13. Frendreis, S. G. V., Skujins, T., and Cesnik, C. E. S., "Six-Degree-of-Freedom Simulation of Hypersonic Vehicles," AIAA Atmospheric Flight Mechanics Conference & Exhibit, August 2009, AIAA 2009-5601.
14. Falkiewicz, N.J., and Cesnik, C.E.S., "A Reduced-Order Modeling Framework for Integrated Thermo-Elastic Analysis of Hypersonic Vehicles," Proceedings of the 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA, May 2009, AIAA 2009-2308.
15. Oppenheimer, M.W., Skujins, T., Doman, D.B., and Cesnik, C.E.S., "Canard-Elevon Interactions on a Hypersonic Vehicle," Proceedings of the AIAA Atmospheric Flight Mechanics Conference and Exhibit, Honolulu, Hawaii, August 2008, AIAA 2008-6383**.**
16. Skujins, T., Cesnik, C.E.S., Oppenheimer, M.W., and Doman, D.B., "Applicability of an Analytical Shock/Expansion Solution to the Elevon Control Effectiveness for a 2-D Hypersonic Vehicle Configuration," Proceedings of the AIAA Atmospheric Flight Mechanics Conference and Exhibit, Honolulu, Hawaii, August 2008, AIAA 2008-6384
17. Oppenheimer, M.W., Skujins, T., Bolender, M.A., and Doman, D.B., "A Flexible Hypersonic Vehicle Developed With Piston Theory," Proceedings of the AIAA Atmospheric Flight Mechanics Conference and Exhibit, Hilton Head, South Carolina, August 2007, AIAA 2007-6396.

Driscoll: (24)

1. A Scramjet Engine Model Including Effects of Precombustion Shocks and Dissociation", S. Torrez, N. Scholten, D. Micka, J. F. Driscoll, M. Bolender, DB Doman, M. Oppenheimer, AIAA Paper 2008-4619.

2. Scramjet Engine Model MASIV: Role of Mixing, Chemistry and Wave Interaction. Torrez, S., Driscoll, J.F., Dalle, D, Micka, D., AIAA Paper 2009-4939
3. Heat Release Distribution in a Dual-Mode Scramjet Combustor – Measurements and Modeling. Micka, D., Driscoll, J.F., Torrez, S., AIAA Paper 2009-7362.
4. Preliminary Design Methodology for Hypersonic Engine Flowpaths. Torrez, S., Driscoll, J.F., Dalle, D., Fotia, M., AIAA Paper 2009-7289
5. Hypersonic Vehicle Thrust Sensitivity to Angle of Attack and Mach Number, Torrez, S., Driscoll, J.F., Dalle, D., Bollender, M., Doman D., AIAA 2009-6152
6. Reduced-Order Modeling of Reacting Supersonic Flows in Scramjet Nozzles, Dalle, D, Fotia, M. Driscoll, J.F., AIAA Paper 2010-6958
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4. Major Model or Algorithms Releases
Cesnik: HSV simulation
Driscoll: MASTRIM and MASIV (AFRL/RBCA, AFRL/RZ,NASA Ames, Boeing, Ohio State University)
Girard/Kabamba: Base Defense, 2013.
Frazzoli: RRT*, SMP, gpuRRT* open-source libraries http://ares.lids.mit.edu/software/ (RRT* received the best Open Source Software award at the 2010 Robotics: Science and Systems conference), RRT* Module in the current release of ROS, OMPL, and MoveIt.

5. Research Summaries
Research summaries for all years are included in attachment.

MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

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Abstract

In its seventh and eighth years, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) had two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on four main issues: (i) the design, modeling, analysis and control of flapping wing vehicles as a new platform for collaborative UAV missions; (ii) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; (iii) distributed, dynamic, sequential, combinatorial and/or stochastic mission planning; and (iv) path planning and flight control to achieve autonomy in contested environments. 2. Air-Breathing Hypersonic Vehicles (ABHV), which focuses on two main issues: (i) operability limits, controllability and uncertainty input to an adaptive control model of hypersonic vehicles; and (ii) adaptive control of hypersonic vehicles.

Status/Progress

<u>**Cooperative Control of Unmanned Air Vehicles**</u>

Optimal Configuration of Alarm Sensors for Monitoring Mobile Ergodic Markov Phenomena on Arbitrary Graphs (Las Fargeas, Niendorf, Kabamba, Girard): Motivated by persistent monitoring tasks, this work considers the placement of alarm sensors incapable of long-distance communication on arbitrary graphs and the selection of the rates of their revisits (by an external agent) to monitor a mobile phenomenon whose movements occur on a graph and are modeled as an ergodic Markov chain. The alarm sensors can be placed on nodes and edges in the graph and act as both sensors and classifiers (i.e., they make a classification decision about the presence of the phenomenon based on a measurement of their surroundings). An approach to design the classifier for each alarm sensor is provided and methods to fuse the measurements of colocated alarm sensors are given. Sensor placement problems to optimize Fisher information, probability of misclassification, or the penalty incurred by poor detections, missed detections, and false alarms are formulated. Approaches to solve the formulated problems for the different optimization criteria are provided. Characteristics of these approaches are described and their merits are discussed. The sensors' revisit rates are selected by matching the recurrence times of the phenomenon at the sensor locations. The different approaches are illustrated through simulations. (IEEE Sensors Journal. Vol.15, No.6, pp. 3622 - 3634, June 2015. doi:10.1109/JSEN.2015.2395416)

Pursuit–Evasion Games in the Presence of Obstacles (Oyler, Girard, Kabamba): This paper studies planar pursuit–evasion games in the presence of obstacles that inhibit the motions of the players. The goal is to construct the dominance regions, where a point in the plane is said to be dominated by one of the players if that player is able to reach the point before the opposing players, regardless of the opposing players' actions. The key achievements of the paper are to provide the dominance regions and to show that an analysis of dominance provides a complete solution to the game. This paper also presents a study of the effects of obstacles by comparing the dominance regions in the presence and absence of obstacles. The obstacles considered include line segments and polygons as well as obstacles that have asymmetric effects on the players. As part of the discussion, a novel, multiplayer pursuit–evasion game is also presented. It features three players on two teams, and it can be used to model rescue scenarios and biological behaviors. The solution of this game cannot be determined from the previous literature, but the methods provided in this paper are used to determine dominance and solve the game. (Automatica. Vol. 65, March 2016, pp. 1-11. doi:10.1016/j.automatica.2015.11.018)

Stability and Criticality Analysis for Integer Linear Programs With Markovian Problem Data (Las Fargeas, Niendorf, Kabamba, Girard): This paper presents the stability and criticality analysis of integer linear programs with respect to perturbations in stochastic data given as Markov chains. These perturbations affect the initial distribution, the transition matrix, or the stationary distribution of Markov chains. Stability analysis is concerned with obtaining the set of all perturbations for which a solution remains optimal. This paper gives expressions for stability regions for perturbations in the initial distribution, the transition matrix, the stationary distribution, and the product of elements of the transition matrix and the stationary distribution. Furthermore, criticality measures that describe the sensitivity of the objective function with respect to an element of the problem data are derived. Stability regions that preserve the stochasticity of the problem data are given. Finally, stability regions for perturbations of elements of the transition matrix, given that the problem is not linear in the initial distribution or the transition matrix, are obtained using a small perturbation analysis. The results are applied to sensor placement problems and numerical examples are given. (IEEE Transactions on Automatic Control. Vol. 61, No. 6, June 2016, pp. 1466-76. doi: 10.1109/TAC.2015.2465271)

Stability of Solutions to Classes of Traveling Salesman Problems (Niendorf, Kabamba, Girard): By performing stability analysis on an optimal tour for problems belonging to classes of the traveling salesman problem (TSP), this paper derives margins of optimality for a solution with respect to disturbances in the problem data. Specifically, we consider the asymmetric sequence-dependent TSP, where the sequence dependence is driven by the dynamics of a stack. This is a generalization of the symmetric non sequence-dependent version of the TSP. Furthermore, we also consider the symmetric sequence-dependent variant and the asymmetric non sequence-dependent variant. Amongst others these problems have applications in logistics and unmanned aircraft mission planning. Changing external conditions such as traffic or weather may alter task costs, which can render an initially optimal itinerary suboptimal. Instead of optimizing the itinerary every time task costs change, stability criteria allow for fast evaluation of whether itineraries remain optimal. This paper develops a method to compute stability regions for the best tour in a set of tours for the symmetric TSP and extends the results to the asymmetric problem as well as their sequence-dependent counterparts. As the TSP is NP-hard, heuristic methods are frequently used to solve it. The presented approach is also applicable to analyze stability regions for a tour obtained through application of the k-opt heuristic with respect to the k-neighborhood. A dimensionless criticality metric for edges is proposed, such that a high criticality of an edge indicates that the optimal tour is more susceptible to cost changes in that edge. Multiple examples demonstrate the application of the developed stability computation method as well as the edge criticality measure that facilitates an intuitive assessment of instances of the TSP. (IEEE Transactions on Cybernetics, Vol. 46, No. 4, pp 973-985, April 2016. doi:10.1109/TCYB.2015.2418737)

Efficient Collision Checking in Sampling-based Motion Planning via Safety Certificates (Bialkowski, Otte, Karaman, Frazzoli): Collision checking is considered to be the most expensive computational bottleneck in sampling-based motion planning algorithms. We introduce a simple procedure that theoretically eliminates this bottleneck and significantly reduces collision checking time in practice in several test scenarios. Whenever a point is collision checked the normal (expensive) way, we store a lower bound on that point's distance to the nearest obstacle. The latter is called a "safety certificate" and defines a region of the search space that is guaranteed to be collision free. New points may forgo collision-checking whenever they are located within a safety certificate of an old point. Testing the latter condition is accomplished during the nearest-neighbor search that is already part of most sampling-based motion planning algorithms. As more and more points are sampled, safety certificates asymptotically cover the search space and the amortized complexity of (normal, expensive) collision checking becomes negligible with respect to the overall runtime of sampling-based motion planning algorithms. Indeed, the expected fraction of points requiring a normal collision-check approaches zero, in the limit, as the total number of points approaches infinity. A number of extensions to the basic idea are presented. Experiments with a number of proof-of-concept implementations demonstrate that using safety certificates can improve the performance of sampling based motion planning algorithms in practice. The International Journal of Robotics Research, 2016 DOI:10.1177/1081286510367554 http://mms.sagepub.com

RRT^X: Asymptotically Optimal Single-Query Sampling-Based Motion Planning with Quick Replanning (Otte, Frazzoli): Dynamic environments have obstacles that unpredictably appear, disappear, or move. We present the first sampling-based replanning algorithm that is asymptotically optimal and single-query (designed for situation in which *a priori* offline computation is unavailable). Our algorithm, RRT^X, refines and repairs the *same* search-graph over the *entire* duration of navigation (in contrast to previous single-query replanning algorithms that prune

and then regrow some or all of the search-tree). Whenever obstacles change and/or the robot moves, a graph rewiring *cascade* quickly remodels the existing search-graph and repairs its shortest-path-to-goal sub-tree to reflect the new information. Both graph and tree are built directly in the robot's state space; thus, the resulting plan(s) respect the kinematics of the robot and continue to improve during navigation. RRT^X is probabilistically complete and makes no distinction between local and global planning, yet it reacts quickly enough for real-time high-speed navigation though unpredictably changing environments. Low information transfer time is essential for enabling RRT^X to react quickly in dynamic environments; we prove that the information transfer time required to inform a graph of size n about an ε-cost decrease is O (n log n) for RRT^X —faster than other current asymptotically optimal single-query algorithms (we prove RRT* is Ω (n(n/ log n $)^{1/D}$) and $RRT^\#$ is ω (n $\log^2$ n). In static environments RRT^X has the same amortized runtime as RRT and RRT*, and is faster than $RRT^\#$. In order to achieve O (log n) iteration time, each node maintains a set of O (log n) expected neighbors, and the search-graph maintains ε-consistency for a predefined ε. Experiments and Simulations confirm our theoretical analysis and demonstrate that RRT^X is useful in both static and dynamic environments.

Air-Breathing Hypersonic Vehicles

a) **Ascent Trajectories of Hypersonic Aircraft: Operability Limits Due to Engine Unstart**
(Ref: Derek J. Dalle, James F. Driscoll and Sean M. Torrez, J. of Aircraft 52, 4, 2015 p. 1345.)

A generic waverider-type hypersonic aircraft that undergoes an ascent trajectory has been modeled using a first principles reduced-order model. Two types of operability limits are added that represent boundaries on the aircraft trajectory map (of vehicle altitude versus Mach number). These boundaries are associated with engine unstart and ram–scram transition. The predicted unstart boundary is to be avoided; the ram–scram transition is a condition through which the aircraft must fly, but it is useful for the control system to know when this transition is approached to account for possible sudden changes in thrust and moments. The model shows that unstart occurs if the aircraft flies too high, too slow, or at too great of an acceleration. The unstart limit can be avoided by selecting a trajectory having sufficiently large dynamic pressure or a low vehicle acceleration. Optimizing these factors avoids an excessive value of the fuel–air ratio that is required for trim. The model also identifies an engine inlet geometry that avoids unstart. To assess the model, the computed results are compared to some available experiments.

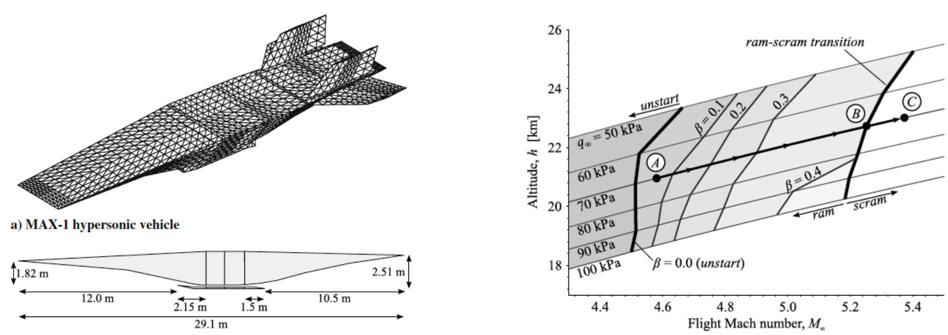

Figure 1. The MAX-1 generic hypersonic vehicle and the computed engine unstart limits on Flight Corredor Map.

b) **Minimum-Fuel Ascent of a Hypersonic Vehicle Using Surrogate Optimization**
(Ref.: Derek J. Dalle, Sean M. Torrez, James F. Driscoll, Michael A. Bolender, and Kevin G. Bowcutt, J. of Aircraft 51, 6, 2014, p. 1973.)

A general strategy is identified to compute the minimum fuel required for the ascent of a generic hypersonic vehicle that is propelled by a dual-mode ramjet–scramjet engine with hydrogen fuel. The study addresses the ascent of an accelerator vehicle rather than a high-speed cruiser. Two general types of ascent trajectories are considered: acceleration within scramjet mode, and acceleration across the ramjet–scramjet transition boundary maximum acceleration and maximum dynamic pressure (lowest allowed altitude) were shown to be near optimum for scramjet

mode trajectories, but optimized trajectories were found to be more complex when both modes are considered. The first-principles model used in this paper computes the combustion efficiency using finite-rate chemistry and a fuel–air mixing model. It also computes the inlet efficiency with a shock wave interaction code, and thus avoids empirical formulas for efficiency that were used in previous models.

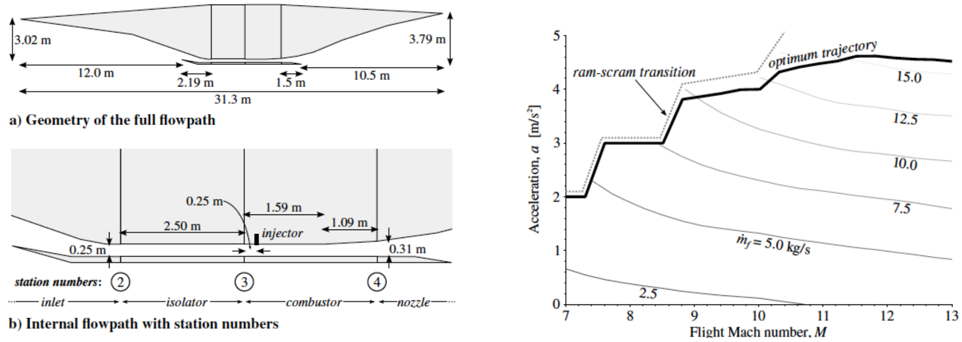

Figure 2. Flow path of the dual mode ramjet-scramjet propulsion system integrated into the MAX-1 vehicle, and the optimum trajectory (acceleration versus flight Mach number during a constant q ascent) that minimized fuel required.

It was found that a generic hypersonic vehicle could be trimmed along many ascent trajectories, and its performance could be computed and optimized. This has not been presented previously with a first-principles model with this level of fidelity. To do so, it was necessary to combine the MASTrim and MASIV codes that were developed by the authors. The resulting model is a significant improvement over previous efforts because it uses first-principles conservation equations to compute the inlet efficiency (including shock wave interactions), the combustion efficiency (based on finite rate chemistry and a fuel–air mixing model), and the nozzle efficiency. It was found that trajectories with minimum total fuel consumption may be fairly complex for cases including transition from subsonic combustion (ram mode) to supersonic combustion (scram mode). Because of lower airspeeds in the combustor during subsonic combustion, ram-mode operation tends to produce more thrust for the same amount of fuel. As a result, optimized trajectories were shown to favor strategies to keep the engine in ram-mode operation as longas possible.

When operating in scram mode, maximum acceleration combined with maximum dynamic pressure was found to be a good heuristic for a true optimized trajectory in most cases. However, the maximum acceleration was not found to be associated with a fuel–air equivalence ratio of unity. In general, the acceleration is limited by the availability of oxygen. If a small portion of the fuel burns, this may result in equivalence ratios above 1.0. This excess fuel is potentially beneficial because it can be used for film cooling of the walls. Flying at a higher dynamic pressure leads to lower trim angle of attack and lower flight-path angle, which lowers the drag coefficient, and thus total fuel consumption for an ascent trajectory. By replacing time with velocity as the variable of integration in the trajectory fuel consumption calculation, it was possible to derive an informative condition for the optimum acceleration. The result indicates that the maximum acceleration is optimal when the acceleration is not a smooth function of fuel mass flow rate and it slightly below the maximum acceleration otherwise. This was consistent with the results of directly optimizing the acceleration profile.

c) **Combustion Efficiencies and Flameout Limits Computed for a Hypersonic Vehicle During Ascent** (Ref: Chukwuka C. Mbagwu, James F. Driscoll, Derek J. Dalle, Sean M. Torrez, AIAA paper 2016-0914 to be submitted for journal publication).

Computations were performed to understand several propulsion tradeoffs that occur when a hypersonic vehicle travels along an ascent trajectory. Operability limits are plotted that define a narrow allowable flight corridor on a plot of altitude versus flight Mach number. Two operability limits are set by the requirements that combustion efficiency exceeds 0.90 and that flameout be avoided. Ambient gas pressure decreases during the ascent, which slows the finite-rate chemistry in the combustor. However, this can be offset by the increases in flight Mach number that increases the gas temperature in the combustor. A surprising finding is that fuel-air equivalence ratio (ER) plays

an unexpected role in controlling flameout limits and combustion efficiency. This is because ER is determined by the trim requirements set by vehicle thrust, drag and acceleration. New aspects of the work are that operability limits are computed for a waverider that is trimmed at each altitude. Also, the MASIV model includes finite-rate chemistry, 3-D mixing, ram-scram transition and an empirical value of the flameout Damkohler number. A reduced-order modeling approach is justified (instead of exact CFD) because all vehicle forces had to be computed over 1800 times to generate multi-dimensional performance maps. Trajectories were optimized to achieve highest combustion efficiency while not crossing flameout limits. The optimum number of wall fuel injectors also was explored.

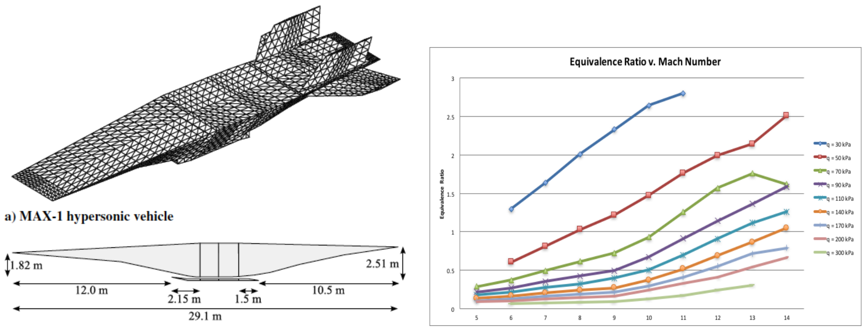

Figure 3. MAX-1 Hypersonic vehicle and the computed fuel-air equivalence ratio (ER) required to trim the vehicle, to provide sufficient thrust to balance all forces and moments during ascent.

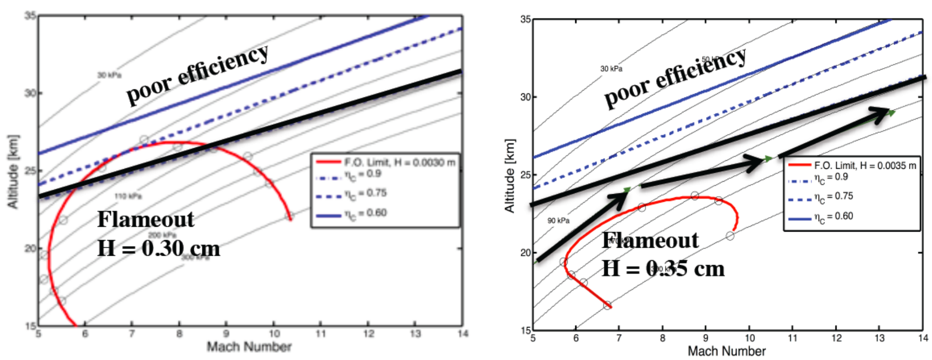

Figure 4. Operability Limits due to Flameout (red line) and Combustion Efficiency Exceeding 0.90 (thick solid line) plotted on a Flight Corredor Map. Cavity flameholder height H is: (a) 0.30 cm and (b) 0.35 cm. Thin solid lines are trajectories of constant q. Vehicle acceleration = 2 g's.

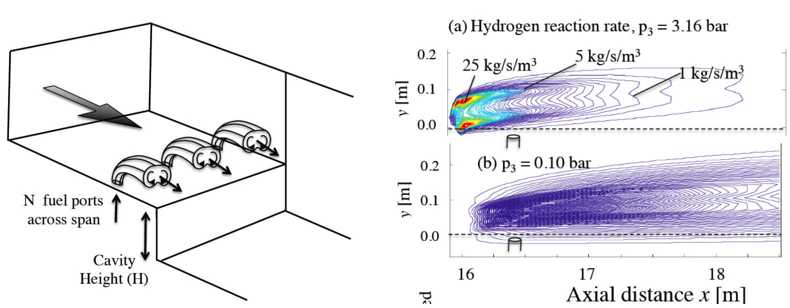

Figure 5. Schematic of three of the 19 fuel jets in the air cross flow within the MAX-1 dual mode ramjet-scramjet engine. Empirical scaling laws are used to rapidly compute combustion efficiency and flameout limits during the ascent trajectory using the reduced order model called MASIV.

A methodology is presented to compute two operability limits that affect the ascent of a trimmed hypersonic vehicle that is powered by dual-mode ramjet-scramjet engine. One is the flameout limit and the other is the limit where combustion efficiency exceeds 0.90. A reduced-order model called MASIV was used that includes finite-rate chemistry tables that are similar to those used in the code FLUENT. A 3-D turbulent mixing model uses empirical formulas for the profiles of mean fuel concentrations in jets in a cross flow. It also applies a conventional assumed-PDF approach to model turbulent mixing.

One new aspect is that the vehicle is trimmed at each altitude so the ER is To evaluate the model an assessment case was run. For this case there was no ascent and each of the four governing variables (p3, T3, U3 and ER) was systematically varied. The resulting trends were in qualitative agreement with previous experiments. For the ascent case, multi-dimensional maps were generated by running the MASIV model 2,000 times, which is the product of 20 different altitudes along each of 10 different trajectories and 10 angles of attack. Each trajectory has a different dynamic pressure. The ten values of angle of attack were necessary to find the trim angle that balances all vehicle forces and moments.

From the maps, the two operability limits were computed that define a narrow flight corridor on a plot of altitude versus flight Mach number. The optimum trajectory was identified as the one that has maximum combustion efficiency and avoids the flameout limit. While results of the assessment case (no ascent) were easy to explain, some results for the ascent case were not expected; they arise due to competing effects of four parameters (p3, U3, T3 and ER). During the ascent the combustor entrance pressure p3 drops and U3 increases, which has the adverse effect of tending to slow the chemistry and reduce the residence time. However, ascent also causes T3 and ER increase, which tends to speed up the chemistry.

An unexpected result is that a high-altitude (low dynamic pressure) trajectory is best to avoid flameout. While a high-altitude trajectory causes low pressures to occur the combustor, the trim requirements impose near-optimum stoichiometric fuel-air ratios that are far from the lean flameout limit. It was found that there is an optimum number of fuel ports (N) that can be located across the engine span. A larger number of ports creates more fuel jets, which tends to increase the surface area for mixing. However, since the overall ER is fixed, the momentum of each jet is reduced, and this tends to reduce mixing area. While the ROM results are only approximate, they do successfully predict several measured flameout limit trends (which ones ?). To determine the flameout limits the aerodynamic and thrust forces are computed approximately 1800 times. That is, for each of six trajectories twenty altitudes are selected. For each altitude fifteen angles of attack are selected to find the one that trims the vehicle. For this type of optimization study a ROM gives a useful first look at the small subset of conditions that should be investigated later using CFD.

A Proper Orthogonal Decomposition (POD) algorithm was developed to reduce the size of the chemistry lookup table matrix from 29 million elements to less than 1% of this number and speed up the computation. Retaining only the largest four POD modes introduced only a 1% inaccuracy since nearly all of the table elements that were eliminated have negligibly small values.

d) **Design and Optimization of Combined Active and Passive Thermal Protection System in a Scramjet-Powered Hypersonic Vehicle**

(Ref: Christopher D. Marley and James F. Driscoll, submitted for the 2017 AIAA SciTech Forum, 9-13 January 2017)

An efficient aerodynamic heating and thermal protection system model are added to MASIV, a reduced-order model of a generic scramjet-powered hypersonic vehicle. The MASIV code was selected over similar engineering-level models because of its advanced combustion model, as heat addition to the combustor walls is often the largest source of heating in hypersonic air-breathing vehicles. The thermal protection system consists of passive insulation and active cooling with the liquid hydrogen fuel acting as the cooling agent. Recent work by Doman investigates different architectures for active cooling in high-speed turbojet

aircraft and optimizes the vehicle and flight trajectory considering heating. This research extends Doman's work to a hypersonic vehicle. Also, the MASIV code used in this study is higher-fidelity than the model Doman developed, allowing for design and optimization considerations that were neglected.

Updates for Professor Annaswamy are provided in the following document.

Despite repeated requests by phone and email, no updates were provided by Professor Deng.

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Final Invention Report

Sequential Loop Closure Based Adaptive Output Feedback Autopilot Design for Hypersonic Vehicles *

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Air Force Research Lab Autonomous Control Branch

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Air-breathing hypersonic vehicles are a topic of significant research interest due to their ability to produce high specific impulse and for their usefulness in the military, commercial, and space industries. As with most conventional flight vehicles, there are many uncertainties which must be accommodated when designing a controller for a hypersonic vehicle. The tight coupling between the engine and airframe, high temperature effects, and the limited availability of wind tunnel and CFD data are some of the challenges unique to the control of air-breathing hypersonic vehicles. This high level of model uncertainty present in hypersonic vehicles makes adaptive control an excellent candidate for ensuring stability and providing reference trajectory tracking during flight.

The design of most flight control systems is broken into several smaller control problems, using modal and timescale separation to allow for the design of reduced order inner-loop controllers which provide stability and desirable damping characteristics. Outer-loop guidance controllers are then used to provide tracking of the desired flight path. While such a sequential loop closing technique has been applied for decades to design flight control systems, little has been done to extend this approach to include adaptive controllers, which are typically used on either the inner or outer loop only. The goal of the proposed research is to develop new inner-loop state and output feedback adaptive controllers for hypersonic vehicles, and an outer-loop controllers which can be used in conjunction with the existing inner-loop designs. Such an approach will allow for the design of reduced order controllers, and provide adaptation to accommodate model uncertainty. In particular, we propose the use of closed-loop reference models in the outer-loop to suitably modify the inner-loop reference to ensure smooth tracking of commands.

I. Introduction

A. Hypersonic Vehicles

With a history spanning well over a half century, hypersonic flight continues to be a topic of significant research interest.[1–5] Air-breathing hypersonic vehicles are particularly attractive due to their potential to serve as high speed passenger transports, long range weapon delivery systems, and provide cost-effective access to space. Hypersonic vehicles are likely to be inherently unstable[6–8] and the integration of the airframe and engine in an air-breathing hypersonic vehicle contributes to additional modeling and control challenges. With limited wind tunnel data, harsh and uncertain operating environments, poorly known physical models, and largely varying operating conditions, it is of great importance to ensure that any control scheme will be significantly robust to ensure safe operation during flight.

*Final report, "Michigan/AFRL Collaborative Center in Control Sciences (MAX)", Grant/Contract Number: 3002085646, OSP # 6924558, Sponsor: University of Michigan.

Unlike the transition from subsonic to supersonic flow, the physics of hypersonic flow do not differ from that of supersonic flow. Instead, the distinction of hypersonic flow is made to stress the importance of certain physical phenomena which exist in all supersonic flows that become dominant at hypersonic speeds, typically defined to be flow at a Mach number of 5 or greater.[9] The high flight Mach numbers experienced by a hypersonic vehicle result in significant aerodynamic heating. Additionally, the engines of air-breathing hypersonic vehicles are tightly integrated into the airframe of the vehicle, where long fore and aft sections of the vehicle typically make up large portions of the engine inlet and nozzle, respectively. This tightly couples the engine dynamics with the airframe and structural dynamics as well as the aerodynamics.[10] The physics of hypersonic flow and these resulting interactions between all the components of the vehicle make the control of hypersonic vehicles very challenging.

An additional challenge associated with the control of air-breathing hypersonic vehicles is the limited ability to accurately determine the aerodynamics characteristics.[11–14] With the presence of such tight coupling between all aspects of a hypersonic vehicle, and extreme flow velocities and temperatures, the ability to collect wind tunnel and flight test data to study these interactions is very difficult, as is CFD. Because of this, much of the knowledge about a hypersonic vehicle's aerodynamics must come from physics-based models. This makes accurate determination of the aerodynamic characteristics very difficult, making the design of a controller more difficult as well. Any control design must be sufficiently robust to accommodate these inevitable uncertainties, and adaptive control is very well suited for application on hypersonic vehicles.

B. Flight Control

The purpose of aerial platforms typically involves navigating along some desired trajectory from a point of origin to a destination, carrying passengers and cargo, performing surveillance, or delivering a weapon. The movement of the vehicle along this trajectory is typically broken into a hierarchy of two tasks. The first task constitutes *flight control* and involves the generation of vehicle forces and moments to achieve some equilibrium condition, as measured by inertial sensors such as rate gyros and accelerometers. The second is *guidance* and involves the action of these forces and moments to move the aircraft along a desired course, as measured by a compass, GPS, or other device. For simple aerial platforms these tasks are accomplished by a human pilot. However, since the emergence of the first autopilot, these functions have been increasingly performed by mechanical and electrical systems. Many modern aircraft, such as the hypersonic vehicles considered here, are completely autonomous with respect to their guidance and control.

The design of a complete controller for most aerial platforms is typically accomplished by solving first the problem of control, followed by that of guidance. The function of the *inner-loop* is to address the task of flight control by commanding the primary flight controls, which are aerodynamic surfaces which enable controlling forces and moments to be applied to the aircraft to induce pitch, roll, yaw. The goal of the inner-loop is to provide stability, desired damping characteristics, and reference tracking of quantities such as roll rate or vertical acceleration. The purpose of the *outer-loop* is to generate the necessary inner-loop commands to ensure the aircraft follows its desired trajectory.

Historically, flight control and autopilot design has used classical, sequential loop closing techniques to synthesize the inner and outer-loop feedback control laws. These control laws are typically designed separately for the longitudinal and lateral-directional dynamics, as these dynamics are decoupled under most flight conditions.[15] Furthermore, timescale separation could be employed to further reduce the order of the control problem. When closing each successive loop, practical experience and root locus techniques are used to determine how to feed back each specific measured signal such as pitch rate or angle of attack to a particular control surface. In doing this, the aircraft could be given desirable handling qualities and admit precise tracking of a pilot's command.

These conventional flight control techniques are typically predicated on precise and accurate knowledge of the aerodynamic characteristics of the aircraft, and designed with sufficient margins to accommodate any uncertainties encountered during flight. However, when design flight controllers for modern aircraft such as hypersonic vehicles, obtaining accurate values of the aerodynamic characteristics is much more challenging. This has led to an increased use of adaptive techniques to solve flight control problems, with great success.[16] Many of these adaptive controllers have focused only on the problem of inner-loop control: e.g. tracking reference commands in angle of attack or roll angle.[17,18] This inner-loop design procedure enabled the design of lower order controllers to provided stability in the presence of uncertainty, but have not allowed for reference tracking of meaningful flight trajectories (such as commanded velocity, altitude, latitude, longitude). Other approaches have used higher order models to represent the vehicle dynamics to allow reference tracking of such flight trajectory commands as velocity and altitude.[19]

C. Report Overview

The benefits of adaptive control in providing stability in the presence of parametric uncertainties, and those of sequential loop closure in providing reduced order controllers applicable to existing vehicles and capable of accommodating inner-loop command limiting were the motivation for investigating a sequential loop closure based adaptive control approach for hypersonic vehicles. As a part of this research, the inner-loop adaptive designs for hypersonic vehicles were investigated first. The work began with state-feedback adaptive controllers in References [17, 18], and output-feedback adaptive controllers in References [20,21] and is presented in Section II. The sequential loop closing problem was first presented for the state feedback case in Reference [22] and is presented in Section III. Future research will extend the sequential loop closure based adaptive control approach to the case of output feedback.

II. Inner-Loop Control Problem

Consider the following MIMO uncertain open-loop system which represents the dynamics of a hypersonic vehicle

$$\begin{aligned} \dot{x}_p &= A_p x_p + B_p \Lambda (u + \Psi_p^\top x_p) \\ y_p &= C_p x_p \\ z_p &= C_{pz} x_p + D_{pz} \Lambda (u + \Psi_p^\top x_p) \end{aligned} \tag{1}$$

where $A_p \in \mathbb{R}^{n_p \times n_p}$, $B_p \in \mathbb{R}^{n_p \times m}$, $C_p \in \mathbb{R}^{\ell \times n_p}$, $C_{pz} \in \mathbb{R}^{n_e \times n_p}$, $D_{pz} \in \mathbb{R}^{n_e \times m}$ are constant *known* matrices. The nonsingular matrix $\Lambda \in \mathbb{R}^{m \times m}$ is diagonal, and $\Psi_p \in \mathbb{R}^{m \times n_p}$, which represents constant matched uncertainty weights which enter the system through the columns of B, are *unknown*. y_p is the *measured* output, and z_p is the *regulated* output, and the number of regulated outputs cannot exceed the number of inputs, that is $n_e \leq m$.

The inner-loop control goal is to design a control input u which will make the inner-loop output z_p track the reference command $z_{p,\text{cmd}}$ with bounded errors in the presence of the uncertainties Λ and Ψ_p. Typically z_p is a body angular rate or linear acceleration. In order to provide command tracking, we introduce integral action, and for this purpose an additional state x_e is defined as

$$\dot{x}_e = z_{p,\text{cmd}} - z_p \tag{2}$$

This integral error state is appended to the plant in (1) leading to the following augmented open-loop dynamics

$$\begin{aligned} \begin{bmatrix} \dot{x}_p \\ \dot{x}_e \end{bmatrix} &= \begin{bmatrix} A_p & 0 \\ -C_{pz} & 0 \end{bmatrix} \begin{bmatrix} x_p \\ x_e \end{bmatrix} + \begin{bmatrix} B_p \\ -D_{pz} \end{bmatrix} \Lambda (u + \Psi_p^\top x_p) + \begin{bmatrix} 0 \\ I \end{bmatrix} z_{p,\text{cmd}} \\ \begin{bmatrix} y_p \\ x_e \end{bmatrix} &= \begin{bmatrix} C_p & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} x_p \\ x_e \end{bmatrix} \end{aligned} \tag{3}$$

The system in (3) can be written more compactly as follows

$$\begin{aligned} \dot{x} &= Ax + B\Lambda(u + \Psi^\top x) + B_{\text{cmd}} z_{p,\text{cmd}} \\ y &= Cx \end{aligned} \tag{4}$$

where $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $B_{\text{cmd}} \in \mathbb{R}^{n \times n_e}$, and $C \in \mathbb{R}^{p \times n}$ are the known matrices given by

$$A = \begin{bmatrix} A_p & 0_{n_p \times n_e} \\ -C_{pz} & 0_{n_e \times n_e} \end{bmatrix} \quad B = \begin{bmatrix} B_p \\ -D_{pz} \end{bmatrix} \quad B_{\text{cmd}} = \begin{bmatrix} 0_{n_p \times m} \\ I_{n_e \times n_e} \end{bmatrix} \quad C = \begin{bmatrix} C_p & 0_{\ell \times n_e} \\ 0_{n_e \times n_p} & I_{n_e \times n_e} \end{bmatrix}$$

and $\Psi = [\ \Psi_p^\top \quad 0_{m \times n_e}\ ]^\top$ is unknown. Note that $p = \ell + n_e$. The underlying problem here is to design a control input u in (4) so that the closed-loop system has bounded solutions and z_p tends to z_{cmd} with bounded errors in the presence of the uncertainties Λ and Ψ.

A. State Feedback

Given the uncertain aircraft dynamics in (4), we first consider the design of a controller when the state is accessible for measurement. Thus, the inner-loop state feedback problem is to design a controller for the uncertain system in (4) when $C = I$, the identity matrix.

1. *Baseline Controller*

We first describe the baseline control design for the nominal case when there are no uncertainties present, that is when $\Lambda = I$ and $\Psi = 0$. Propose the following baseline control law

$$u_{\text{bl}} = K_x^\top x \tag{5}$$

where K_x is selected such that $A + BK_x^\top$ is Hurwitz. This gain K_x can be selected using LQR or other state-space control technique to provide the desired baseline performance and stability margins.

2. *Adaptive Controller*

With the baseline controller determined as above, the next step is to design an adaptive controller in the presence of $\Lambda \neq I$ and $\Psi \neq 0$. Suppose we augment the nominal controller in (5) as

$$u = \big(K_x + \Theta(t)\big)^\top x \tag{6}$$

where $\Theta(t)$ is to be determined by a suitable update law. The reference model is given by

$$\dot{x}_m = A_m x_m + B_m z_{p,\text{cmd}} + L(x_m - x) \tag{7}$$

where $A_m = A + BK_x^\top$ is a Hurwitz matrix. This reference model will provide the nominal response which will be used in calculating the tracking error $e = x - x_m$ which will drive adaptation. The error dynamics are given by

$$\dot{e}_x = (A_m + L)e_x + B\Lambda\widetilde{\Theta}^\top x \tag{8}$$

By selecting the following update law

$$\dot{\Theta} = \text{Proj}_\Gamma(\Theta, -\Gamma x e^\top PB\text{sign}(\Lambda)) \tag{9}$$

the system can be shown to be globally stable for all bounded command inputs $z_{p,\text{cmd}}$.[17,18]

The authors' research in References [17, 18] investigated the performance of this controller applied to a six degree-of-freedom generic hypersonic vehicle during angle of attack and roll commands, when subject to a loss of control effectiveness, stability derivative uncertainties, and CG shifts, while in the presence of sensor noise, and input delay. A gain-scheduled robust baseline state feedback inner-loop controller was designed and augmented with an adaptive component to contend with the various uncertainties. The adaptive controller exhibited improved performance and stability over the baseline controller when given a commanded trajectory in the presence of parametric uncertainties. This adaptive augmented gain-scheduled baseline control architecture maintained stable flight given certain uncertainties when the baseline control alone could not.

B. Output Feedback

Unlike subsonic and supersonic aircraft, the sensors used obtain the incidence angle measurements, angle of attack and sideslip, cannot be implemented on a hypersonic vehicle as they protrude into the free stream flow and would burn up during flight. For this reason, these measurements must be derived by some other means, resulting in incidence angle measurements which can contain significant bias. Because the normal operation of the engine depends on the angle of attack and sideslip, a constant bias in the measurement can cause the vehicle's engine to experience unstart if this sensor is used for feedback control. In order to avoid sensor-bias-triggered unstart, the measurement signals which are known to have a high level of corruption may not be used, thus necessitating an output feedback approach. Thus, the inner-loop output feedback problem is to design a controller for the uncertain system in (4) when $C \neq I$.

A controller along the lines of References [23–25] is proposed, as it leads to a low order robust controller. This controller includes a Luenberger observer together with LQR feedback control gains. As our ultimate goal is to develop an adaptive controller which in turn requires a reference model, we propose a control design where the reference model has components of an observer as well. In particular, we introduce a feedback component into the reference model, with the corresponding feedback gain L chosen similar to a Luenberger gain, that is, so that it ensures adequate stability margins for the nominal closed-loop system. The resulting reference model is referred to as a closed-loop reference

model (CRM) which has been shown recently to result in highly desirable transient properties[26–29] and is described as follows:

$$\begin{aligned}\dot{x}_m &= A_m x_m + B_{\text{cmd}} z_{p,\text{cmd}} + L(y_m - y)\\ y_m &= C x_m\end{aligned} \tag{10}$$

where $A_m = A + BK_x^\top$ and K_x is selected such that A_m is Hurwitz. Furthermore, K_x should be selected to provide the desired closed-loop performance of the nominal system. With such a K_x, we can propose the following baseline controller that can guarantee command tracking and a certain amount of stability margins for the nominal closed-loop system.

$$u_{\text{bl}} = K_x^\top x_m \tag{11}$$

1. *Adaptive Controller*

With the baseline controller determined as above, the next step is to design an adaptive controller in the presence of $\Lambda \neq I$ and $\Psi \neq 0$. Suppose we augment the nominal controller in (11) as

$$u = \big(K_x + \Theta(t)\big)^\top x_m \tag{12}$$

where $\Theta(t)$ is to be determined by a suitable update law. The question is if the introduction of the parameter Θ as in (12) is sufficient to accommodate the parametric uncertainties. For this purpose, we introduce a matching condition as described in Remark 1 below.

Remark 1 The selection of the reference model state matrix as $A_m = A + BK_x^\top$ guarantees the existence of a parameter Θ^* that satisfies the following matching condition.

$$A_m = A + B\Psi^\top + B\Lambda\big(\Theta^{*\top} + K_x^\top\big)$$

where Θ^* is given by

$$\Theta^{*\top} = (\Lambda^{-1} - I)K_x^\top - \Psi^\top$$

In summary, the problem that is addressed in this research is the determination of an adaptive augmented robust baseline output feedback controller as in (12) to control the plant in (4) using the CRM/Observer as in (10). This in turn necessitates finding an adaptive law for adjusting Θ in (12) and the observer gain L in (10). The main tools used for determining the adaptive controller involve the Kalman-Yakubovich[30] and matrix elimination lemmas,[31] which help reduce the problem of finding L to a state feedback problem of a related lower order subsystem.

We next introduce the process for selecting the CRM gain L in (10) and the update law for Θ in (12). To accomplish the goal of reference tracking we take an approach which focuses on the error between the closed-loop plant and the reference model states, as opposed to each of these trajectories individually. Thus, the goal of reference tracking can be ensured by appropriately selecting the update law to drive this state error to zero. Similarly, we consider the error between the parameter Θ in (12) and Θ^* in Remark 1. The resulting state tracking error and parameter error, respectively, can be defined as

$$\begin{aligned}e_x &= x - x_m\\ \widetilde{\Theta} &= \Theta - \Theta^*\end{aligned}$$

The problem of finding an adaptive law for Θ that guarantees stability depends on the relationship between the two errors above. This relation, denoted as *error model*, in turn provides cues for determining the adaptive law. In the problem under consideration, the underlying error model can be described as

$$\begin{aligned}\dot{e}_x &= (A + LC + B\Psi^\top)e_x + B\Lambda\widetilde{\Theta}^\top x_m\\ e_y &= Ce_x\end{aligned} \tag{13}$$

where e_y is the measured output error. As mentioned earlier, the problem of finding a stabilizing adaptive controller is equivalent to finding an L and an adaptive law for adjusting $\widetilde{\Theta}$ in (13). Determining a stable adaptive law for an error model as in (13) relies on properties of an underlying transfer function that is SPR.[30] However, the definition of SPR

is restricted to square transfer functions. As such, for these properties to be applicable to the error model in (13), a suitable static postcompensator $S_1 \in \mathbb{R}^{m\times p}$ has to be chosen such that

$$S_1 C(sI - A - LC - B\Psi^\top)^{-1}B \in \mathbb{R}_p^{m\times m}(s)$$

where $\mathbb{R}_p(s)$ denotes the ring of *proper* rational transfer functions with coefficients in $\mathbb{R}$. That is the underlying transfer matrix is square, and therefore can be evaluated in terms of SPR properties. We therefore introduce a synthetic output error e_s as

$$e_s = S_1 C e_x$$

With this postcompensator, the underlying error model is modified as

$$\begin{aligned} \dot{e}_x &= (A + LC + B\Psi^\top)e_x + B\Lambda\widetilde{\Theta}^\top x_m \\ e_s &= S_1 C e_x \end{aligned} \tag{14}$$

Thus, the design of an output feedback adaptive controller is reduced to selecting matrices $S_1 \in \mathbb{R}^{m\times p}$ and $L \in \mathbb{R}^{n\times p}$ such that the error dynamics in (14) are SPR. Under some mild assumptions about the plant in (4) S_1 and L are guaranteed to exist. A process for synthesizing these matrices is given in the authors' work in References [20,21] where the problem is reduced to solving a reduced order state-feedback problem, ultimately guaranteeing the feasibility of an LMI which is then solved numerically. The resulting controller provides global stability and command tracking of $z_{p,\text{cmd}}$ by z_p with bounded errors in the presence of the uncertainty.

III. Outer Loop Sequential-Loop Closure Approach

The preceding section provided the problem formulation and a solution for the inner-loop adaptive control problem, both for the state and output feedback cases. The solution to the inner-loop control problem yields controllers which provide global stability for all bounded command inputs $z_{p,\text{cmd}}$, where $z_{p,\text{cmd}}$ is selected as an inner-loop variable such as a vehicle angular rate. The challenge in designing the outer-loop then is to determine what $z_{p,\text{cmd}}$ should be in order to enforce reference tracking of a third output $z_{g,\text{cmd}}$. For example, when controlling a hypersonic vehicle, this might be the specification of the pitch rate command so the vehicle will climb to a desired altitude. The challenge with sequential loop closing adaptive control is the nonlinear interaction between the inner and outer loops.

Consider following linear uncertain system

$$\begin{aligned} \begin{bmatrix} \dot{x}_p \\ \dot{x}_g \end{bmatrix} &= \begin{bmatrix} A_p + B_p\Psi_p^\top & B_{gd} \\ B_{gp} & A_g \end{bmatrix} \begin{bmatrix} x_p \\ x_g \end{bmatrix} + \begin{bmatrix} B_p\Lambda \\ 0 \end{bmatrix} u \\ \begin{bmatrix} y_p \\ y_g \end{bmatrix} &= \begin{bmatrix} C_p & 0 \\ 0 & C_g \end{bmatrix} \begin{bmatrix} x_p \\ x_g \end{bmatrix} \\ \begin{bmatrix} z_p \\ z_g \end{bmatrix} &= \begin{bmatrix} C_{pz} + D_{pz}\Psi_p^\top & 0 \\ 0 & C_{gz} \end{bmatrix} \begin{bmatrix} x_p \\ x_g \end{bmatrix} + \begin{bmatrix} D_{pz}\Lambda \\ 0 \end{bmatrix} u \end{aligned} \tag{15}$$

where $A_p \in \mathbb{R}^{n_p\times n_p}$, $A_g \in \mathbb{R}^{n_g\times n_g}$, $B_p \in \mathbb{R}^{n_p\times m}$, $B_{gp} \in \mathbb{R}^{n_g\times n_p}$, $B_{gd} \in \mathbb{R}^{n_p\times n_g}$, $C_p \in \mathbb{R}^{\ell_p\times n_p}$, $C_g \in \mathbb{R}^{\ell_g\times n_g}$, $C_{pz} \in \mathbb{R}^{n_{ep}\times n_p}$, $C_{gz} \in \mathbb{R}^{n_{eg}\times n_g}$, and $D_{pz} \in \mathbb{R}^{n_{ep}\times n_p}$ are *known* matrices and where $\Lambda \in \mathbb{R}^{m\times m}$ and $\Psi_p \in \mathbb{R}^{n_p\times m}$ are *unknown*. The outputs y_p and y_g represent all of the sensors which are available for measurement, and the regulated outputs z_p and z_g represent the outputs which we would like to enforce tracking of a command signal $z_{p,\text{cmd}}$ and $z_{g,\text{cmd}}$, and the number of regulated outputs cannot exceed the number of inputs, that is $n_{ep} \leq m$. The *control goal* is to first design the input u in (16) so that z_p tracks $z_{p,\text{cmd}}$ and then design $z_{p,\text{cmd}}$ so that z_g tracks $z_{g,\text{cmd}}$.

We can partition the system in (15) into the uncertain inner-loop dynamics, and the known outer-loop dynamics. The inner-loop dynamics in (1) can be given more generally as follows, by including the extra outer-loop terms.

$$\begin{aligned} \dot{x}_p &= A_p x_p + B_p(\Lambda u + \Psi_p^\top x_p) + B_{gd}x_g \\ y_p &= C_p x_p \\ z_p &= C_{pz}x_p + D_{pz}(\Lambda u + \Psi_p^\top x_p) \end{aligned} \tag{16}$$

The outer-loop dynamics are given by

$$
\begin{aligned}
\dot{x}_g &= A_g x_g + B_{gp} x_p \\
y_g &= C_g x_g \\
z_g &= C_{gz} x_g
\end{aligned}
\tag{17}
$$

Applying integral action to the open-loop dynamics in (16) as we did with (4) and combining with the outer-loop guidance dynamics as given by (17) we have the following system

$$
\begin{aligned}
\dot{x} &= Ax + B(\Lambda u + \Psi^\top x) + B_{\text{cmd}} z_{p,\text{cmd}} + B_d x_g \\
\dot{x}_g &= A_g x_g + B_g x \\
y &= Cx \\
y_g &= C_g x_g
\end{aligned}
\tag{18}
$$

We introduce the inner-loop reference model similar to that in (10) as

$$
\begin{aligned}
\dot{x}_m &= A_m x_m + B_{\text{cmd}} z_{p,\text{cmd}} + L(y_m - y) + B_d x_g \\
y_m &= C x_m
\end{aligned}
\tag{19}
$$

and an additional outer-loop reference model

$$
\begin{aligned}
\dot{x}_{gm} &= A_g x_{gm} + B_g x_m + L_y(y_m - y) + L_g(y_{gm} - y_g) \\
y_{gm} &= C_g x_{gm}
\end{aligned}
\tag{20}
$$

where $L_y \in \mathbb{R}^{n_g \times p}$, and $L_g \in \mathbb{R}^{n_g \times p_g}$. The outer-loop error is given by

$$
\begin{aligned}
e_g &= x_g - x_{gm} \\
e_{gy} &= y_g - y_{gm}
\end{aligned}
$$

and the goal is to design an outer-loop controller such that $\lim_{t\to\infty} e_g(t) = 0$, which will thus enforce outer-loop, guidance tracking as desired. Combining the inner-loop reference model in (10) and the outer-loop reference model in (20) we obtain the combined reference model as

$$
\begin{bmatrix} \dot{x}_m \\ \dot{x}_{gm} \end{bmatrix} = \begin{bmatrix} A_m & 0 \\ B_g & A_g \end{bmatrix} \begin{bmatrix} x_m \\ x_{gm} \end{bmatrix} + \begin{bmatrix} B_{\text{cmd}} \\ 0 \end{bmatrix} r + \begin{bmatrix} L \\ L_y \end{bmatrix} (y_m - y) + \begin{bmatrix} 0 \\ L_g \end{bmatrix} (y_{gm} - y_g) + \begin{bmatrix} B_d \\ 0 \end{bmatrix} x_g \tag{21}
$$

Next the forward-loop controller which generates the reference model input r from the outer-loop command signal and stabilizes (21) is designed.

A. Forward Loop Control Design

A controller of the follow form is selected

$$
\begin{aligned}
\dot{x}_{fm} &= A_{fm} x_{fm} + B_{f1} z_{g,\text{cmd}} + B_{f2} x_{gm} + B_{f3} x_m \\
r &= C_{fm} x_{fm} + D_{f1} z_{g,\text{cmd}} + D_{f2} x_{gm} + D_{f3} x_m
\end{aligned}
\tag{22}
$$

Substituting the forward-loop controller (22) into (21) gives the following

$$
\begin{bmatrix} \dot{x}_m \\ \dot{x}_{gm} \\ \dot{x}_{fm} \end{bmatrix} = \begin{bmatrix} A_m + B_{\text{cmd}} D_{f3} & B_{\text{cmd}} D_{f2} & B_{\text{cmd}} C_{fm} \\ B_g & A_g & 0 \\ B_{f3} & B_{f2} & A_{fm} \end{bmatrix} \begin{bmatrix} x_m \\ x_{gm} \\ x_{fm} \end{bmatrix} + \begin{bmatrix} B_{\text{cmd}} D_{f1} \\ 0 \\ B_{\text{cmd}} \end{bmatrix} z_{g,\text{cmd}} + \begin{bmatrix} L \\ L_y \\ 0 \end{bmatrix} (y_m - y) + \begin{bmatrix} 0 \\ L_g \\ 0 \end{bmatrix} (y_{gm} - y_g) + \begin{bmatrix} B_d \\ 0 \\ 0 \end{bmatrix} x_g \tag{23}
$$

which can be represented more compactly as

$$
\dot{\bar{x}}_m = \bar{A}_m \bar{x}_m + \bar{B}_{\text{cmd}} z_{g,\text{cmd}} - \bar{L}_y e_y - \bar{L}_g e_{gy} + \bar{B}_d x_g \tag{24}
$$

where appropriate selection of the controller in (22) ensures that $\bar{A}_m$ in (24) is Hurwitz. The command input to the plant in (18) is modified with an outer-loop error feedback term as follows

$$z_{p,\text{cmd}} = r + S_g e_{gy} \tag{25}$$

where $S_g \in \mathbb{R}^{n_{ep} \times p_g}$. The proposed control architecture is represented in following block diagram

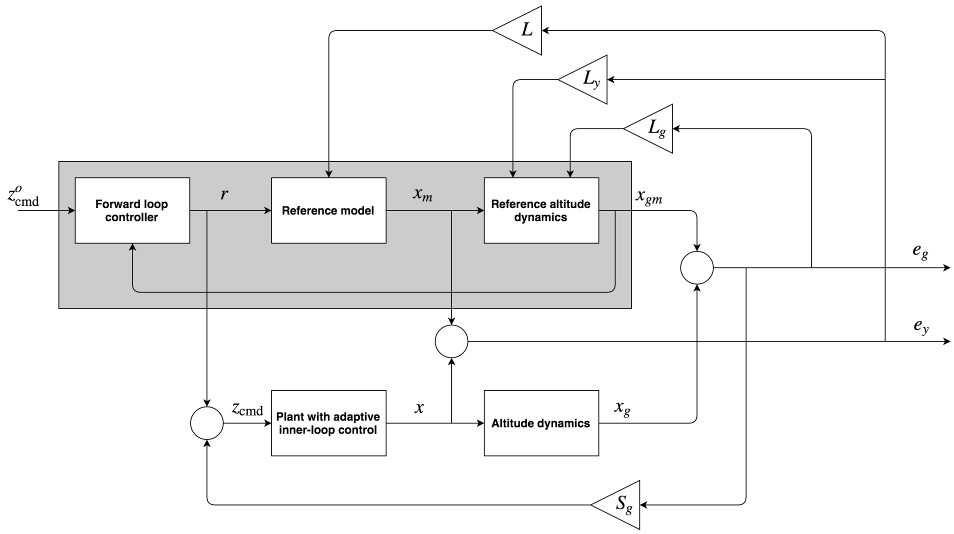

Figure 1. Complete integrated inner and outer-loop design block diagram

B. Solving for Outer-Loop Controller Parameters: State Feedback

For the case of state feedback let $C_p = I$ and $C_g = I$ in (15). The inner-loop error dynamics for the state-feedback case were given in (8) and stability of the closed loop system results from using the update law in (9). In order to ensure stability when the additional guidance loops are closed, we consider the outer-loop error dynamics as well, given by subtracting (18) from (20) as follows

$$\dot{e}_g = (A_g + L_g)e_g + (B_g + L_y)e_x \tag{26}$$

L_g in (26) is selected to ensure $A_g + L_g$ is Hurwitz to enforce stability of the outer-loop error dynamics. We set $S_g = 0$ in (25) and select the matrix L_y as

$$L_y = -B_g \tag{27}$$

It is this choice of L_y which modifies the outer-loop guidance portion of the reference model in response to errors within the inner loop. It is this feature which enables stability of the combined inner and outer loops, and provides command tracking of altitude at the outer loop. The stability of the complete system using the adaptive inner-loop and sequential loop closure procedure to close the outer loop is given in Reference [22].

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

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Abstract
In its sixth year, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) has two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on four main issues: (i) the design, modeling, analysis and control of flapping wing vehicles as a new platform for collaborative UAV missions; (ii) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; (iii) distributed, dynamic, sequential, combinatorial and/or stochastic mission planning; and (iv) path planning and flight control to achieve autonomy in contested environments. 2. Air-Breathing Hypersonic Vehicles (ABHV), which focuses on two main issues: (i) operability limits, controllability and uncertainty input to an adaptive control model of hypersonic vehicles; and (ii) adaptive control of hypersonic vehicles.

Status/Progress

<u>**Cooperative Control of Unmanned Air Vehicles**</u>

Cooperative Surveillance and Pursuit (Las Fargeas, Hyun, Girard, Kabamba): This work is motivated by intelligence, surveillance, and reconnaissance missions without automated target recognition where multiple unmanned aerial vehicles (UAVs) rely on unattended ground sensors (UGS) to monitor a road network. The UGS cannot communicate with each other, thus the UAVs are tasked with persistently visiting the UGS to gather information. The UGS keep track of the time a target passed by their location. The UAVs are assumed to be controlled by a single centralized authority; they travel at a constant velocity or can loiter above intersections, while the target's velocity along the roads follows a given probability distribution over a bounded range. In previous work, an algorithm to coordinate the unmanned aerial vehicles during surveillance and pursuit of targets was given. The current problem treated is that of placing the unattended ground sensors and selecting their revisit rates such that the UAVs can reliably and quickly detect targets. The selection of the sensor parameters is performed using a model of target movements generated from prior information. The problem is formulated, multiple objective functions for selecting the configuration of the sensors are presented, and methods to maximize these objective functions are derived. Furthermore, the effectiveness of these methods are illustrated through simulation.

Perpetual Flight on Flow Fields (Bencatel, Girard, Kabamba): Atmospheric flow field phenomena, such as thermal updrafts, wind shear, and gusts, hold large amounts of energy. Aircraft may harvest some of this energy by executing static and dynamic soaring flight paths. These paths usually require good flight maneuverability. Most small UAVs have better maneuverability than larger UAVs and many other aircraft, and are able to execute the maneuvers required to harvest energy from the flow field phenomena. This work discusses the flow field phenomena characteristics, analyzes the necessary conditions to achieve perpetual flight with the different flow field phenomena and shows how these phenomena can be observed. We study and develop detailed flow field models and their interactions with the aircraft dynamics. For thermal updrafts we created a new Bubble Thermal model, including its movement and its interactions with the surrounding flow field. We also extended an existing Chimney Thermal model to include movement and interactions with the surrounding flow field. In terms of wind shear we created three models for the Layer Wind Shear phenomenon and a model for the Ridge Wind Shear phenomenon. These models serve as inputs to the inference methods used to localize and characterize the air flow phenomena. Further, we analyze what is the required balance between each flow field phenomenon's characteristics and the aircraft

aerodynamic characteristics to enable perpetual flight. The result is intuitive, showing that it is easier to perform perpetual flight with more efficient aircraft and stronger phenomena, as an updraft or a flow gradient. We noticed a lack of experimental validation of existing phenomena models. As such, we developed control methods that would allow us to use UAVs to collect spatially distributed data to enable the validation of the phenomena models. We studied collision avoidance and formation flight methods and implemented them to allow safe environment sampling and also collaborative flight. The developed algorithms are based on hybrid systems and sliding mode control. The formation flight controller presented a good performance, with good path tracking and, even more importantly, maintaining a safe distance among the formation aircraft throughout the flight.

Homing Guidance with Binary Range-Rate Measurements (Oyler, Girard, Kabamba): In this work we consider the problem of planar homing guidance for a vehicle with a known heading angle, traveling to a beacon with unknown location, and using only a measurement of binary range-rate. That is, the vehicle only knows whether it is getting closer to or farther away from the beacon. We develop a planar homing guidance law utilizing a sliding mode controller and an observer. This guidance law does not require knowledge of the vehicle's location, the closest points of approach for multiple headings, or the time history of measurements. We also present this guidance law's response to multiple initial conditions and corrupted measurements. This approach provides a method of low-cost, autonomous homing-guidance that utilizes a single, omnidirectional receiver to guide a vehicle to a single, omnidirectional transmitting beacon.

Reactive Mission Planning in Challenging Environments (Niendorf, Girard, Kabamba): Unmanned aerial vehicles are widely used for intelligence, surveillance and reconnaissance missions where a set of targets needs to be visited. This motivates research on persistent visitation, task allocation and multi-vehicle coordination within the controls community. Typically, these problems are treated as specializations of the well-known traveling salesman problem or vehicle-routing problem. However, unmanned aerial vehicles operate in dynamic environments with changing exogenous forces. Thus, the question whether a solution remains optimal after changes to the environment occurred needs to be addressed. By integrating tactical and path planning using updated path cost information, mission planning becomes dynamic. Instead of optimizing the task schedule every time path costs alter, we derive stability regions for solutions to a prototypical UAV mission, the traveling salesman problem. In particular, we derive expressions for the stability region and edge cost tolerances for the best tour from a set of tours using a linear programming relaxation of a novel zero-one integer programming formulation of a *p*-tours problem. Hereby, we obtain a polynomial time method, to determine whether a tour remains optimal after arbitrary changes are made to the travel costs between arbitrary city pairs. This result is then specialized to the solution obtained through application of the *k*-opt heuristic with arbitrary values for *k*.

Minimum-violation Mission Planning under Temporal-Logic Specifications (Reyes-Castro, Karaman, Frazzoli): Previous work in MACCCS made numerous contributions to the problem of planning complex missions, defined by temporal-logic constraints. However, in realistic situations it may be the case in which there is no plan satisfying all the constraints, e.g., due to conflicting specifications, or adverse environmental conditions. In such a case, an algorithm returning no solution is of limited use, especially when not all constraints are of equal importance. For example, some specifications may encode "hard" constraints (no-flight zones, rules of engagement, etc.), while others may be merely "soft" constraints, e.g., expressing operator preferences, or optional objectives. To address this problem, we developed a class of "minimum violation" planning algorithms, which provides a systematic approach to return a solution that ensures that as many "high-priority" constraints as possible are satisfied. In a number of papers, we provided algorithms for synthesizing control strategies for dynamical systems with differential constraints to fulfill a given task specification while satisfying as many specifications as possible from a prioritized set of rules. Ideas behind sampling based motion-planning algorithms, such as the Probabilistic Road Map (PRM) and Rapidly-exploring Random Tree (RRT), are employed to incrementally construct a finite *concretization* of the dynamics as a durational Kripke structure. In conjunction with this, a finite automaton that captures the safety rules is used in order to find an optimal trajectory that minimizes the violation of mission specifications. The proposed algorithms guarantee asymptotic optimality, i.e., almost-sure convergence to optimal solutions, and are amenable to real-time implementation, as demonstrated on computational examples, as well as a ground vehicle operating on public roads.

Persistent Patrolling with Adversarial Observations (Root, Frazzoli): As the use of UASs in military operations becomes more widespread, our adversaries are developing new strategies to cope with the US technological advantages—often using extremely cheap and low-tech approaches to neutralize state-of-the-art systems. For

example, operational experience in, e.g., Afghanistan, as well as recent findings in Al-Qaeda hideout in Mali, makes it clear that the adversary has routinely adopted different strategies when faced with patrolling aircraft. In this work, we aim at developing new strategies for patrolling against a smart adversary. The majority of persistent patrolling strategies seek to minimize the time between visits or "idleness" of any target or location within an environment in an attempt to locate a hidden adversary as quickly as possible. Such strategies generally fail, however, to consider the game-theoretic impacts of the adversary seeking to avoid the patroller's detection. The interplay between the patrollers and the adversary created a non-collaborative game setting where each player would employ the best response to the other's strategy. The field of patrolling security games that addresses this two-player game is maturing with several authors posing the patrolling scenario as a leader-follower Stackelberg game where the adversary chooses to attack at a location and time as a best response to the patroller's policy. We model the adversary as capable of collecting a sequence of local observations who must use this information to determine the optimal time to attack. This work proposes to find the optimal patrolling policy in different environments given this adversary model. Teams of patrolling agents following this optimal policy achieve a higher capture probability, and we can determine the marginal improvement for each additional patroller. A paper on the topic is still in preparation.

Incremental Randomized Value Iteration for Approach-Evasion Differential Games (Mueller, Zhu, Frazzoli): Building on the success of recent work within MAX, i.e., the development of RRT* and derivative algorithms, we developed new incremental sampling-based algorithms to approximate optimal policies in differential games. Approximate dynamic programming has proven an invaluable tool for the numerical solution of such games, and the proposed method provides an incremental, probabilistically complete alternative to traditional, grid-based algorithms. The main advantage of our algorithms is their anytime property: in other words, the proposed algorithms generate good approximations of optimal (saddle-point) policies very quickly, and asymptotically converge to globally optimal ones. Theoretical properties of the algorithm are investigated, primarily in the context of differential pursuit-evasion games, in terms of (asymptotic) soundness, completeness, and saddle-point optimality. Results from simulation on a large number of benchmark examples show that the proposed methods yields solutions that are comparable with those from state-of-the-art algorithms, with the additional advantage that good policies are available within a very short computation time, without requiring a fine discretization of the state space, thus demonstrating the applicability of the proposed algorithms to high-dimensional problems that would be intractable using standard dynamic programming. In our most recent paper, we consider an approach-evasion differential game where the inputs of one of the players are upper bounded by a random variable. The game enjoys an order preserving property, whereby a larger relaxation of the random variable induces a smaller value function. Two numerical computation algorithms are proposed to asymptotically recover the expected value function. The performance of the proposed algorithms is compared via a stochastically parametric homicidal chauffeur game.

Electromagnetic Actuator for Flapping Wing Micro Air Vehicle (Deng): In our previous work, the design and construction of a 2.6 gram electromagnetic actuator operated at resonance was presented. This design was based on wedge-shaped electromagnetic coil generating a driving torque on a magnet embedded rotor. Additional permanent magnets are used to create virtual springs, supplying a restoring torque to the rotor and creating nonlinear system stiffness. Flapping wing parameters were varied systematically to generate 16 unique wing profiles for fabrication. Independent bench tests for the coil and spring magnets were used to modify analytical models of the actuator. Based on the equations of motion, estimates for the primary mode of resonance and the peak to peak stroke amplitude were determined. Frequency response test were conducted on the flapper using the test wings at varying supply voltages and spring configurations to verify predicted resonate frequencies and amplitudes. Wing kinematics and mean lift measurements were made for the flapper operating at resonance, producing a lift-to-weight ratio of over one at 24V. A full theoretical framework for optimizing electromagnetic flapping-wing actuation mechanism was derived. Expressions for the mean coefficient of lift, stroke average lift force, and theoretical efficiency were determined. The developed framework was used to investigate the feasibility and performance of the proposed actuator at different scales, showing that lift-to-weight ratios of above two are possible at smaller scales. This work is currently in use in the design of a miniaturized robot at approximately 1/3 scale of the original actuator capable of achieving flapping frequencies in access of 130 Hz. Frequency responses were studied near resonance for a two actuator system. Varying the separation between two actuators, wing kinematics were captured using high speed video. A strong interaction torque as discovered and modeled assuming dipole moment models for each rotor. An ideal separation and magnetic polarity between actuators was determined, resulting in an extended driving torque curve and increased stroke amplitude. Using the results of the optimization and torque interaction experiments, the actuator was reconfigured to reduce weight and to create prototype robot. The improvements include the relocation of the stopper and spring magnets and an improved trapezoidal coil profile constructed from copper clad aluminum

magnetic wire. Guided wire experiments were conducted to show that the complete assembly was capable of producing enough lift to overcome the weight. The complete robot weighs approximately 3.90 grams and capable of an estimated lift-to-weight ratio of 1.3. Force to input mapping and a six degree of freedom system identification of the robot are planned in order to achieve tethered stable hover with on-board feedback.

Direct Drive of Flapping Wings Under Resonance with Instantaneous Wing Trajectory Control (Deng): In previous work, a motor-driven flapping-wing actuator was operated at resonance using a torsion spring. The wing is driven by a DC motor with direct gear transmission. Linear torsion springs mounted on the shaft create restoring torque when the wing is displaced from its mid-stroke position. The actuator dynamics is obtained using system identification. The flapping motion of the wing is achieved by closed-loop motor control. PID and LQR controllers are applied for instantaneous wing kinematics tracking: A PID controller is able to precisely track the trajectory with relatively large control input; on the other hand, a linear quadratic regulator (LQR) achieves large flapping amplitude with small input effort. The mechanism was able to track sinusoidal motions with different amplitude, bias and frequencies, generating roll and pitch torques that can be used for flight control. A Hopf oscillator based central pattern generator is also shown to be an alternative trajectory to track. The proposed wing actuation mechanism provides an at-scale wing testing platform for flapping wing micro aerial vehicles. In current work, a novel nonlinear Adaptive and Robust controller is explored and shown in realistic simulation to provide major performance improvements. These improvements include; 1. Control error is reduced down to 0.05 percentage, 2. Nonlinearity is explicitly estimated and cancelled, 3. Quick on-line parameter estimations convergence, 4. Un-modeled dynamics and disturbances handled with robust control term, 5. The stability and performance are guaranteed with theoretical proof, 6. No control chattering and minimum control efforts. Further simulation has shown that the on-line parameter estimation was able to converge under changing payloads, changes in flight conditions, and other parameter uncertainties. The adaptive robust non-linear controller was shown to be robust, through simulation, for un-modeled disturbances such as wind gusts and additional system modeling errors.

Air-Breathing Hypersonic Vehicles

Hypersonic Vehicle (HSV) Modeling - Propulsion-Vehicle Integration (Driscoll, Cesnik, Falkiewicz, Torrez, Dalle, Bolender, Muse): The goal is to develop a control-oriented model of a hypersonic vehicle with integrated reduced-order submodels of ram-scram propulsion & aero-thermoelasticity. The combined model is used to (a) optimize an ascent trajectory and minimize fuel while varying six control variables, to (b) compute operability limits, including engine unstart and ram-scram transition on an ascent trajectory, to integrate the propulsion and aero-thermoelastity submodels and (d) provide matrices of stability derivatives to controls people at MIT and AFRL. These goals have been achieved for the MAX-1 vehicle, which is X-43-like and operates on hydrogen fuel. The figure shows the vehicle and the trajectory, with computed unstart limit and ram-scram limit. Next year the geometry will be hanged to that of HIFiRE-6, a 3-D shock pattern will be added and the hydrogen fuel will be replaced with more complex ethylene fuel. Another operability limit will be added: the engine flameout limit that occurs if the vehicle flies too high and too fast. Four students on the MAX project working withJ. F. Driscoll graduated with Ph.D. degrees: Sean Torrez, Derek Dalle, Matt Fotia, (leveraged funding from NASA) and Daniel Micka (leveraged funding from DOD). Three archival journal papers appeared or were submitted in 2013 while three appeared previously. Sean Torrez won the 2011 AIAA Gordon Oates Airbreathing Propulsion Graduate Student Award. Sixteen AIAA conference papers were generated by Driscoll's group. Three computer codes were developed; they are MASTRIM, the vehicle trim model that uses Newton impact method for aerodynamic forces on body panels, MASIV, our ram-scramjet propulsion model, and ATE, the aero-thermoelastic model of Prof. Cesnik that computes structural and thermal properties. These codes contain reduced-order models so they can be run in seconds on a single PC processor to trim the vehicle. Validation comparisons to full CFD solutions show that they are accurate to 6% - 10%. It is not possible to run high-fidelity CFD codes 10,000 times to compute many trimmed vehicle trajectories and find an optimum. Control derivatives were computed and were provided to MIT to develop their adaptive control model.

Hypersonic Vehicle Partitioned Solution (Cesnik, Klock): The new hypersonic vehicle (HSV) simulation partitioned solution has undergone several stages of development over the past year. The first stage was the completion of the time marching solution in Matlab using a formulation started the prior year for the NASA Vision vehicle. This Matlab code brought together the aerothermoelastic lifting surface work of Falkiewicz et al., aeroelastic fuselage, and 1D scramjet work of Frendreis and Cesnik to consider a whole hypersonic vehicle by means of partitioned solutions which exchanged information at prescribed times across common interfaces. This

year's key developments were: 1. Development of a flexible HSV trimming routine for steady level flight. The initial fmincon function was replaced by the more discontinuity tolerant fminsearch function while faster and more comprehensive cost functions were developed. These cost functions considered both the rigid body and elastic motions of the HSV main body and lifting surfaces in order to minimize the rate change of the HSV states through control inputs such as angle of attack, lifting surface deflections, and scramjet fuel equivalence ratio. 2. Integration of the Michigan AFRL Scramjet In Vehicle (MASIV) 2D hypersonic propulsion model in the HSV partitioned framework. This was achieved by considering the 3D main body and scramjet cowl as a set of 2D cross sections stacked spanwise across the vehicle. The elastic deformation of the main body near the inlet and nozzle of the scramjet was then used to create flow path geometries that dynamically affected the performance of the propulsion system. Further development of the MASIV code has also allowed the consideration of ramjet to scramjet transition, unstart, and flameout conditions during hypersonic maneuvers. 3. Introduction of kriging surrogate to the MASIV propulsion solution. This surrogate model allows the user to choose to pay a larger up-front cost in terms of time and computation for the trade of faster HSV trimming and simulation thereafter. It is an option to replace the time-consuming MASIV runs directly, and increases robustness of the solution. 4. Generalization of the time marching and trim codes to include hypersonic vehicles beyond the original NASA Vision vehicle. Notable features of this effort were the introduction of the AFRL vehicle design, the separation of the lifting surface solutions into self-contained routines that did not need to be symmetric across the vehicle, and recoding of the propulsive model to consider the pressure contributions onto the main body outer mold line. For the coming year, continue development will focus on increasing the code accessibility and modularity by reformatting it into a subscribe-publish architecture, allowing for multiple fidelity analysis codes to be swapped among themselves. Moreover, the unsteady aerodynamic ROM by Skujins and Cesnik will be implemented into the new framework.

Adaptive Control of Hypersonic Vehicles (Annaswamy): Control of Hypersonic vehicles is an extremely challenging task due to the largely varying operating conditions taking place during flight envelope. Due to the significant changes that occur in the aerodynamics, propulsion, and environmental conditions, and due to the fact that both physics-based models and data-driven models are either inaccurate or too complex, any feedback controller that is introduced in the vehicle has to be suitably advanced. The sophistication in this controller has to be two-fold: first, it has to accommodate large changes that occur in the vehicle dynamics by incorporating adaptive components that have the ability to make on-line changes based on the newly available system measurements. Second, it should possess the ability to ascertain the dynamics that exists at a given operating point and provide a robust compensatory action that ensures safe realization of desired figures of merit. The focus of our project has been on the development of adaptive control strategies for the control of highly uncertain air-breathing hypersonic vehicles so as to realize complex maneuvers. Since MAX began in October 2011, we have developed two adaptive controllers for AFRL's Road Runner generic hypersonic vehicle. The performance of a baseline controller is compared to the same design augmented with one of these two different model-reference adaptive controllers: a classical open-loop reference model design, and modified closed-loop reference model design. Both adaptive controllers show improved command tracking and stability over the baseline controller when subject to uncertainties in control effectiveness, center of gravity location, aerodynamic coefficients, and sensor bias. The closed-loop reference model controller offers the best performance, tolerating a reduced control effectiveness of 50\%, rearward center of gravity shift of -0.9 to -1.6 feet (6-11\% of vehicle length), aerodynamic coefficient uncertainty scaled 4$\times$ the nominal value, and sensor bias of $+$1.6 degrees on sideslip angle measurement. The closed-loop reference model adaptive controller maintains at least 73\% of the delay margin provided by the robust baseline design, tolerating input time delays of between 18-41 ms during 3 degree angle of attack doublet and 80 degree roll step commands. The adaptive controllers accommodate stable flight through engine unstart in some instances when the baseline controller cannot, and further modifications to the adaptive controllers are being investigated to better accommodate flight through unstart. These methods include actuator saturation protection, state limiters, switched control, and sensor bias rejection.

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

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Abstract
In its fifth year, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) has two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on three main issues: (i) the design, modeling, analysis and control of flapping wing vehicles as a new platform for collaborative UAV missions; (ii) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations,; and (iii) distributed, dynamic, sequential, combinatorial and/or stochastic mission planning. 2. Air-Breathing Hypersonic Vehicles (ABHV), which focuses on two main issues: (i) operability limits, controllability and uncertainty input to an adaptive control model of hypersonic vehicles; and (ii) adaptive control of hypersonic vehicles.

Status/Progress

<u>**Cooperative Control of Unmanned Air Vehicles**</u>

Mixed-Initiative Nested Classification (Girard, Hyun, Faied, Kabamba): We propose a novel architecture for a team of machine and human classifiers (i.e., a mixed-initiative team). We adopt a model of performance that is workload-dependent for the human and workload-independent for the machine. The team is structured in a nested architecture that exploits a primary trichotomous classifier (returning true, false, or unknown) with workload-independent performance that turns over the data classified as unknown to a secondary dichotomous classifier (returning true or false) with workload-dependent performance. The novel classifier architecture outperforms a single dichotomous classifier.

1. B. Hyun, M. Faied, P. Kabamba, A. Girard, Optimal Multivariate Classification by Linear Thresholding. American Control Conference, Montreal, Canada, 2012. (invited paper)
2. B. Hyun, M. Faied, P. Kabamba, A. Girard, Mixed-Initiative Nested Classification by Optimal Thresholding, IEEE Conference on Decision and Control, Orlando, FL, 2011.
3. B. Hyun, M. Faied, P. Kabamba, A. Girard, Classification with Synergistic Teams, 18th World Congress of the International Federation of Automatic Control (IFAC), Milano, Italy, 2011.
4. B. Hyun, M. Faied, P. Kabamba, A. Girard, Mixed-Initiative Nested Classification for n Team Members, IEEE Conference on Decision and Control, Maui, HI, 2012, Accepted.

Informative Path Planning by Bond Energy Algorithm (Chang, Hyun, Girard): Autonomous vehicles are often employed to explore an area and collect information from objects of interest. In this work, we consider path planning for an autonomous vehicle in a generalized information collection infrastructure. A novel information collection model that accounts for the vehicle visibility range is proposed which enables the modeling of non-isotropic targets, i.e., targets with unequal information emission rate with respect to the relative position of the vehicle. Finding a feasible solution for such a path-planning problem can be challenging since the problem can be easily over-constrained. Moreover, existing methods, such as the many heuristics for Traveling-Salesman Problem (TSP), may not provide a feasible solution since they do not necessarily account for information-collection objective. The bond energy algorithm, an optimization heuristic that is robust to initial conditions in information collection tasks, is provided. Using these models and techniques, a path-planning algorithm is proposed for an

arbitrarily defined information collection mission. Several sample scenarios are demonstrated, one with objects with isotropic information emission, and the other with non-isotropic emission.

1. Y. Chang, B. Hyun, A.R. Girard, Path Planning for Information Collection Tasks using Bond-energy Algorithm, American Control Conference, Montreal, Canada, 2012.

Persistent Visitation, Detection and Capture (Las Fargeas, Hyun, Girard, Kabamba): A base is surrounded by a network of unattended ground sensors (UGS) meant to detect intruders at intersections on local roads. The UGS cannot communicate with each other or with the base, thus several unmanned aerial vehicles (UAV) are tasked with persistently visiting the UGS to gather information. The UGS keep track of the time an intruder passed by their location. The UAVs have no sensing capabilities and can communicate with an UGS if they are close enough. In addition, the UAVs have finite fuel tanks and can refuel at the base. In this scenario, the UAVs fully refuel when at the base. The UAVs travel at a constant velocity or can loiter. The UAVs are assumed to be controlled by a single centralized authority. The intruder's velocity along the roads follows a given probability distribution over a bounded range. The intruder's velocity may be larger than the UAV velocity. The UAVs' goal is to monitor the network while attempting to capture intruders before they reach the base. In addition, the UAVs must always be carrying a positive amount of fuel. Successful monitoring is accomplished by visiting the UGS as their respective revisit rates dictate (which have been set by a mission designer). A successful capture occurs when an intruder, UGS, and UAV are colocated simultaneously. The UAVs are permitted to miss deadlines. Path planning decisions are made by a weighed minimization of the amount of time by which deadlines are missed and the probability of not capturing an intruder.

1. J. Las Fargeas, B. Hyun, P. Kabamba, A. Girard, Persistent Visitation with Fuel Constraints, 15th Meeting of the Euro Working Group on Transportation (Energy Efficient Transportation Systems 2012), Paris, France, 2012, Accepted.

Perpetual Flight on Flow Fields (Girard, Bencatel): Atmospheric flow field phenomena, such as thermal updrafts, wind shear, and gust, hold large amounts of energy. Aircraft may harvest some of this energy by executing static and dynamic soaring flight paths. These paths usually require good flight maneuverability. Most small UAVs present better maneuverability than larger UAVs and many other aircraft. Thereby, they are able to execute the required maneuvers to harvest energy from the flow field phenomena.

This work discusses the flow field phenomena characteristics, analyzes the necessary conditions to achieve perpetual flight with the different flow field phenomena and shows how these phenomena can be observed. We study and develop detailed flow field models and their interactions with the aircraft dynamics. For thermal updrafts we created a new Bubble Thermal model, including its movement and its interactions with the surrounding flow field. We also extended an existing Chimney Thermal model to include movement and interactions with the surrounding flow field. In terms of wind shear we created three models for the Layer Wind Shear phenomenon and a model for the Ridge Wind Shear phenomenon. These models serve as inputs to the inference methods used to localize and characterize the air flow phenomena.

Further, we analyze what is the required balance between each flow field phenomenon's characteristics and the aircraft aerodynamic characteristics to enable perpetual flight. The result is intuitive, showing that it is easier to perform perpetual flight with more efficient aircraft and when each phenomenon presents stronger effects, as an updraft or a flow gradient.

To enable the flow field energy exploitation, most control methods require an estimate of the exploited phenomenon parameters. We show that the flow field phenomena parameters are observable and derive methods to estimate these parameters. These methods are based on Particle Filters, coping well with the nonlinear nature of the phenomena models and the non-Gaussian probability distributions. The test results are very promising, showing good estimation performance and requiring low processing power.

We noticed a lack of experimental validation of existing phenomena models. As such, we developed control methods that would allow us to use UAVs to collect spatially distributed data to enable the validation of the phenomena models. We studied collision avoidance and formation flight methods and implemented them to allow safe environment sampling and also collaborative flight. The developed algorithms are based on hybrid systems and sliding mode control. The formation flight controller presented a good performance, with good path tracking and, even more importantly, maintaining a safe distance among the formation aircraft throughout the flight.

1. R. Bencatel, J. Sousa, M. Faied and A. R. Girard. Formation Control with Collision Avoidance. Proceedings of the IEEE Conference on Decision and Control, Orlando, FL, 2011.

Provably Correct Mission Planning under Temporal-Logic Specifications (Frazzoli, Karaman): Automatic generation of control programs that satisfy complex missions described using high-level specification languages such as temporal logics has been studied extensively. However, optimality of such control programs, for instance with respect to a cost function, has received relatively little attention. In (Karaman and Frazzoli, ACC2012), we studied the problem of optimal trajectory synthesis for a large class of specifications, given in the form of deterministic μ-calculus. We proposed a sampling-based algorithm, based on the Rapidly-exploring Random Graphs (RRGs), which solves this problem with probabilistic completeness and asymptotic optimality guarantees. We also pointed out connections to (optimal) memoryless winning strategies in infinite parity games, which may be of independent interest. We evaluated our algorithm in a simulation studies involving a kinematic model of a UAV. Our simulation results show that in this scenario the algorithm quickly discovers a trajectory that satisfies the specification, and improves this trajectory towards an optimal one if allowed more computation time.

The Persistent Patrol Problem (Frazzoli): In (Enright and Frazzoli, ACC 2012), we consider the following problem: consider a team of mobile agents, such as UAVs, searching for and visiting target points that appear in a bounded environment according to a stochastic renewal process with a known absolutely continuous spatial distribution. Agents must detect targets with limited-range onboard sensors. It is desired to minimize the expected waiting time between the appearance of a target point, and the instant it is visited. When the sensing radius is small, the system time is dominated by time spent searching, and it is shown that the optimal policy requires the agents to search a region at a relative frequency proportional to the square root of its renewal rate. On the other hand, when targets appear frequently, the system time is dominated by time spent servicing known targets, and it is shown that the optimal policy requires the agents to service a region at a relative frequency proportional to the cube root of its renewal rate. Furthermore, the presented algorithms in this case recover the optimal performance achieved by agents with full information of the environment. Simulation results verify the theoretical performance of the algorithms.

Incremental Randomized Value Iteration for Approach-Evasion Differential Games (Frazzoli, Karaman): Building on the success of recent work within MAX, i.e., the development of RRT* and derivative algorithms, we developed new incremental sampling-based algorithms to approximate optimal policies in differential games. Approximate dynamic programming has proven an invaluable tool for the numerical solution of such games, and the proposed method provides an incremental, probabilistically complete alternative to traditional, grid-based algorithms. The main advantage of our algorithms is their anytime property: in other words, the proposed algorithms generate good approximations of optimal (saddle-point) policies very quickly, and asymptotically converge to globally optimal ones. Theoretical properties of the algorithm are investigated, primarily in the context of differential pursuit-evasion games, in terms of (asymptotic) soundness, completeness, and saddle-point optimality. Results from simulation on a large number of benchmark examples show that the proposed methods yields solutions that are comparable with those from state-of-the-art algorithms, with the additional advantage that good policies are available within a very short computation time, without requiring a fine discretization of the state space, thus demonstrating the applicability of the proposed algorithms to high-dimensional problems that would be intractable using standard dynamic programming. A paper on this subject is in preparation, for submission to ACC 2013.

Flapping Wing Vehicle Dynamics and Analysis (Deng): The current collaborative effort with AFRL/RB has been to implement and test a split cycle constant frequency modulation control strategy on a flapping MUAV. Our group's contribution began this past summer with the design and implementation of the hardware and discrete controller required to track sets of both symmetric and asymmetric wing trajectories that make up the split cycle control strategy. Using two surface mount microprocessors, independent PWM voltages and motor commutations sequences were sent to each flapper motor. The duty cycle of this PWM drive voltage was regulated by a discrete PID controller using a quadrature motor position signal from a MILE encoder on the motor for feedback to accurately track a desired set of wing trajectories. An additional microprocessor was used to receive split cycle control parameters from a hand held RF transmitter and then transmit those commands to each motor's commutator chip. Encoder reversal and skip protection was also incorporated into the discrete PID controller as well as a method to desynchronize and resynchronize the wings during testing. The effectiveness of this hardware and discrete controllers was tested on an optical table and the desired wing trajectories were verified using a high-speed camera.
In order to test the validity of the split cycle control strategy and the effects it has on the flapper's body dynamics, two independent experiments were devised. The first experiment, conducted at AFRL WPAFB, qualitatively examined the effects of split cycle control and wing desynchronization with the flapper operated on an air table. Using a large flat disc mounted on the bottom of the flapper an air table was used to "float" the flapper on a pocket

of air while still allowing for two translational degrees of freedom and one rotational. Video recordings of the flapper flappers translation and rotation where then made while the wings split cycle were varied together and independently. The second set of experiments, conducted at Purdue University, consists of a series of static mounted force experiments with the flapper flapped in air, to measure the total inertial and aerodynamics forces, and in a vacuum chamber, to isolate only the aerodynamic forces. In these experiments the flapper is rigidly mounted to a six-component force/torque sensor, ATI Nano 17, and flapped with both symmetric and asymmetric split cycle wing trajectories. Force and moment data taken from these experiments will then be compared when completed.

Thus far with the force and moment experiments much time has been spent to ensure the quality of the data recorded. The relatively small aerodynamic forces generate from flapping requires a force sensor of high sensitivity; however the noise generated by the large inertial forces and moments of the flapping mechanism creates a poor signal-to-noise ratio in the data. Because of this three independent tests have been run of the each split cycle parameter and flapping frequency. From these three experiments the data is then filtered using a zero phase shift digital Butterworth filter with the break frequency set at five times the flapping frequency. The data is then broken down in to cycles, using an FFT of the data, and fifteen cycles worth of data from each experiment is averaged to ensure the repeatability of each experiment. These fifteen cycles are chosen from the data after the flapper has reached a steady state and eliminate any transient contribution. In addition to the force and moment data, video recording of the flapping have been made to verify that correct wing kinematics are tracked. Experiments for one of the several wings provided by the AFRL group, in a single wing configuration, has been completed in air and the results are presented in the attached power point.

With all the work that has currently been completed, several experiments are needed to completely evaluate split cycle control effects. From the previously described experiments for the flapper in air, a duplicate set of experiments in a vacuum chamber are needed to obtain the only the inertial forces and moments generated by the flapper. These recorded forces and moments will then be subtracted from the air experiments to ideally obtain only the aerodynamic forces. With the single wing configuration tested, a double pair of wings configuration flapped synchronously and asynchronously in air is also needed for comparison with the single wing results. Finally since the AFRL group has provided multiple pairs to test the best wing for this flapper needs to be determined form the set.

Air-Breathing Hypersonic Vehicles

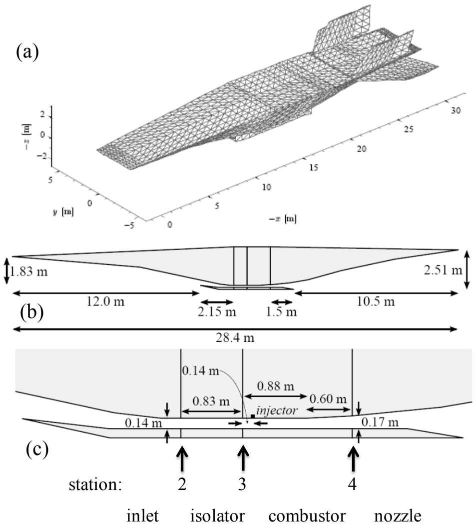
Hypersonic Vehicle Modeling - Propulsion-Vehicle Integration (Driscoll, Torrez, Dalle)

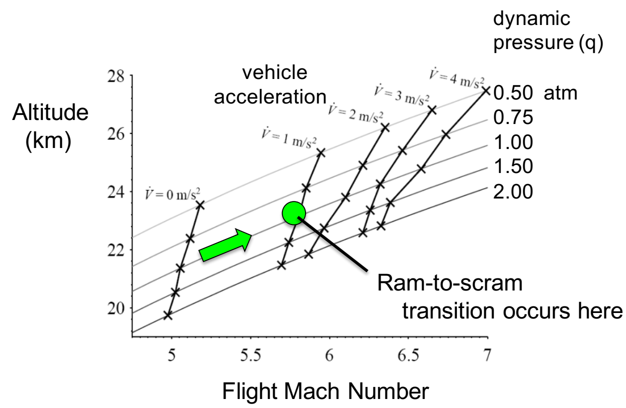
Previously this effort focused on developing a reduced-order model of a hypersonic vehicle that is a significant extension to previous AFRL work. The MASTRIM code (Michigan-AFRL supersonic trim code) considers either an X-43-like or a HIFiRE-6-like vehicle and computes all aerodynamic and thrust forces in less than 2 seconds on a standard PC. It then trims the vehicle in about 20 seconds after iterating to find the correct angle of attack. Then the vehicle is trimmed at each altitude along an ascent trajectory. Many trajectories are considered in order to determine the optimum trajectory that leads to minimum fuel requirements. This optimization work requires thousands of runs, which only can be accomplished with a reduced-order model such as the one we developed; thousands of high fidelity CFD runs would not be practical. If higher fidelity is required, the reduced order model can be used to identify the specific conditions of interest, and a small number of CFD runs can be implemented.

This past year the optimized trajectory was computed and several operability limits were added to the MASTRIM model, including: ram-scram transition, engine unstart margin, and flameout limits. Recently the model was used to compute and to understand the conditions that cause a ram-scram transition for the MAX-1 hypersonic vehicle that undergoes an ascent trajectory from Mach four to Mach eight at a constant dynamic pressure (q). This trajectory is represented by one curve on the Flight Corridor Map (of altitude plotted versus flight Mach number). Transition occurs at one point along this curve, which defines the transition Mach number. The model is used to quantify the sudden jumps in thrust, shock location, and other properties that happen at the ram-scram transition. This information is needed to develop control systems that account for sudden changes at ram-scram transition, unstart and flameout. A series of curves show how the transition boundary depends on governing parameters, including the dynamic pressure, the vehicle acceleration and the inlet compression ratio. The computational method is assessed by comparing predictions to some available measurements.

Next year the focus will be on modifying the geometry to be that of a HiFIRE-6 vehicle that is run on ethylene fuel. Challenges will be to model the 3-D shock interactions in the inlet, to add the complex chemistry

associated with ethylene fuel. Different optimization methods (surrogate and collocation) will be assessed. Six control variables will be systematically varied to produce operating maps.





Left: MAX-1 hypersonic vehicle (a), dimensions (b), and engine flow path (c). Right: Trajectory of the MAX-1 vehicle (arrow) showing where ram-scram transition is predicted (circle). In this case the dynamic pressure (q) is selected to be 1 atm. and the vehicle acceleration is selected to be 1 m/s^2.

Adaptive Control of Hypersonic Vehicles (Annaswamy): Control of Hypersonic vehicles is an extremely challenging task due to the largely varying operating conditions taking place during a flight envelope. Due to the significant changes that occur in the aerodynamics, propulsion, and environmental conditions, and due to the fact that both physics-based models and data-driven models are either inaccurate or too complex, any feedback controller that is introduced in the vehicle has to be suitably advanced. The sophistication in this controller has to be two-fold: first, it has to accommodate large changes that occur in the vehicle dynamics by incorporating adaptive components that have the ability to make on-line changes based on the newly available system measurements. Second, it should possess the ability to ascertain the dynamics that exists at a given operating point and provide a robust compensatory action that ensures safe realization of desired figures of merit. The focus of our project has been on the development of adaptive control strategies for the control of highly uncertain airbreathing hypersonic vehicles so as to realize complex maneuvers.

Over the past nine months, we have developed an adaptive controller for a Generic Hypersonic Vehicle to track high bank-angle reference commands, and high angle of attack commands during climbs and descents in the presence of actuator uncertainties, axial center of gravity location shifts, and stability derivative uncertainties. The adaptive controller is able to maintain excellent tracking with actuator uncertainties up to 40%, rearward CG shift of 5% of the vehicle length, and pitching and yawing moment uncertainties of almost 400%, outperforming a well-designed robust, multivariable, base-line controller. All results were obtained using a high fidelity 6-DOF simulation model of the GHV.

AFRL Points of Contact

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

GRANT NUMBER FA8650-07-2-3744

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Abstract
In its fourth year, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) has two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on two main issues: (i) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; and (ii) dynamic, sequential, combinatorial and/or stochastic mission planning. 2. Air-Breathing Hypersonic Vehicles (ABHV), which focuses on two main issues: (i) development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion and can be used in a 6 DOF flight dynamics simulation; and (ii) determination on appropriately modifying vehicle configuration to improve dynamic controllability without compromising performance. The MAX center also includes funding from the Boeing Company aimed at work in dynamics and control of flapping wing vehicles.

Status/Progress

__Cooperative Control of Unmanned Air Vehicles__

On the Independence of Information and Classification Performance (Girard, Hyun, Faied, Kabamba): The purpose of this research is to show that, in a classifier, increasing the amount of information, in the sense of Shannon, does not necessarily improve classification performance, when classification decisions are made by the likelihood-ratio rule and the classification performance is the probability of misclassification. We investigate such counterintuitive phenomena for classifiers that follow two models: classifiers with workload-independent and with workload-dependent performance. The performance of a classifier is defined by two abilities: recognizing truth out of truth (rate of true positives) and falsehood out of falsehood (rate of true negatives). The paper proves that the counterintuitive phenomena are caused by a trade-off between the two abilities. Work has also happened on classification using synergistic teams, and on mixed-initiative nested classification by optimal thresholding (submitted to CDC 2011). Please refer to publications if interested.

1. B. Hyun, P. Kabamba, M. Faied, and A. Girard, "Classification with Synergistic Teams", 18th World Congress of the International Federation of Automatic Control (IFAC), Milano, Italy, 2011, Accepted.
2. B. Hyun, C.J. Park, W. Wang, and A/.R. Girard, "Heterogeneous Human Operator Team in Classification Tasks: Modeling and Supervisory Control using Discrete Event Systems", Special Issue for the Proceedings of IEEE, 2011, Accepted for publication.

Distributed Assignment and Scheduling (Girard, Jackson): In [1] we presented a constrained distributed scheduling problem and extended a distributed constraint satisfaction method to solve the distributed scheduling problem. This work considered the problem of finding a schedule for the completion of several tasks when the start times of the tasks are constrained relative to each other and knowledge of the problem is distributed across several agents. The constraints considered were black-box constraints, that is, the agents doing the scheduling were assumed to have no prior knowledge of the constraint structure. The algorithm is correct and complete. In [2] we presented a distributed assignment problem whose solution guarantees that distributed scheduling can be performed by the agents given a limited communication topology. This method solves the problem of making an assignment of tasks to agents that respects a clustering restriction dictating that agents assigned certain tasks must be able to communicate. The assignment method takes advantage of a distributed Simulated Annealing principle to find a feasible assignment. These two methods can be used to solve constrained distributed scheduling problems over arbitrary network topologies. We are currently extending the scheduling work in [1] to obtain optimal schedules. In addition, the associated trade-offs in modeling complexity and communication requirements are beings studied.

1. J. Jackson, A. Girard, Distributed Task Scheduling Subject to Arbitrary Constraints, 18th World Congress of the International Federation of Automatic Control (IFAC), Milano, Italy, 2011.
2. J. Jackson, M. Faied, P. Kabamba, A. Girard, Communication-Constrained Distributed Task Assignment, IEEE Conference on Decision and Control, Orlando, FL., 2011, Submitted.

Verifying Coobservability for Dynamic Event Observation and Partial State Perception (Girard, Wang): In many applications of distributed supervisory control, controllers are able to dynamically determine a choice of events to observe and to communicate. Moreover, controllers often detect subsets of state space directly and as they observe event occurrences. In this paper, coobservability verifiers advance existing results by allowing the control system automaton to be other than a subgraph of the uncontrolled system. Techniques for verifying coobservability are in turn advanced as controllers perform both transition-based observation and state perception. Much work has also been done in the areas of language-based minimization of sensor activation for event diagnosis, of optimizing transition-cased information acquisition policies, of online minimization of sensor action for supervisory control. We are omitting a description of these for space reasons, but refer the reader to the publications.

1. W. Wang, A. R. Girard, S. Lafortune, and F. Lin, “On Codiagnosability and Coobservability with Dynamic Observations”, IEEE Transactions on Automatic Control, to appear in Aug. 2011
2. W. Wang, A. R. Girard “An Online Optimizing of Information Acquisition in Supervisory Control and its Application in Smart Power Grids”, accepted by Automatica, 2010, to appear, 2011.
3. W. Wang, C. Gong, and A. R. Girard, “Language-based Minimization of Sensor Activation for Event Diagnosis”, in Proceedings of the 49th IEEE Conference on Decision and Control, Dec. 2010

Sampling-based algorithms for optimal motion planning (Frazzoli, Karaman): During the last decade, sampling-based path planning algorithms, such as Probabilistic Road Maps (PRM) and Rapidly-exploring Random Trees (RRT), have been shown to work well in practice and possess theoretical guarantees such as probabilistic completeness. However, little effort has been devoted to the formal analysis of the quality of the solution returned by such algorithms, e.g., as a function of the number of samples. Karaman and Frazzoli filled this gap, by rigorously analyzing the asymptotic behavior of the cost of the solution returned by stochastic sampling-based algorithms as the number of samples increases. A number of negative results are provided, characterizing existing algorithms, e.g., showing that, under mild technical conditions, the cost of the solution returned by broadly used sampling-based algorithms converges almost surely to a non-optimal value. The main contribution of the effort is the introduction of new algorithms, namely, PRM* and RRT*, which are provably asymptotically optimal, i.e., such that the cost of the returned solution converges almost surely to the optimum.

1. S. Karaman and E. Frazzoli. Sampling-based algorithms for optimal motion planning. Int. Journal of Robotics Research, 2011. To appear.

Humans-in-the-loop queueing systems (Frazzoli, Savla): Formal methods for task management for human operators are gathering increasing attention to improve efficiency of human-in-the-loop systems. Within this research project, we propose a novel dynamical queue approach to intelligent task management for human operators [1,2]. We propose a model of dynamical queue, in which the service time depends on the server utilization history. The proposed queueing model is motivated by widely-accepted empirical laws describing human performance as a function of mental arousal. The focus of the work is to characterize the throughput of the dynamical queue and design corresponding maximally stabilizing task release control policies, assuming deterministic arrivals. We focus extensively on threshold policies that release a task to the server only when the server state is less than a certain threshold. When every task brings in the same deterministic amount of work, we give an exact characterization of the throughput and show that an appropriate threshold policy is maximally stabilizing. The technical tools rely on exploiting the optimality of the class of one-task equilibrium associated with the server dynamics. When the amount of work associated with the tasks is an i.i.d. random variable with finite support, we show that the maximum throughput increases in comparison to the case where the tasks have deterministic amount of work. Finally, we collected and analyzed preliminary empirical data in support of the dynamical queue framework for human operators.

1. K. Savla and E. Frazzoli. Dynamical queue-based task management policies for human operators. In Proc. American Control Conf., 2011. To appear.
2. K. Savla and E. Frazzoli. A dynamical queue approach to intelligent task management for human operators. Proceedings of the IEEE, 2011. Invited paper, to appear.

Optimal "Aiming Off": Stochastic Path Planning with One-Dimensional Features (Frazzoli, Temple): In [1],

we investigated a traditional navigational technique, known as off-course navigation, land-fall intercept, single line-of-position, and aiming off, which has been extensively used by navigators on foot, ancient ships, pre-GPS aircraft, and modern submarines. Using this technique, the navigator deliberately aims to one side of their objective with the intention of following a line feature (e.g., a road, coastline, celestial bearing, or radio beacon) that is known to intersect the objective. Despite its extensive use, the question of how much should one aim off? has never been rigorously addressed. The main difficulty in quantifying the benefit of aiming off is that it entails optimal search as a sub-problem; how does one proceed once the line feature is reached? Our recent work in this project has provided a strong heuristic policy for search on the real line. Given this policy, which we use as a black box, we are able pose the problem of aiming off as a straightforward optimization problem. This problem is relevant not only to path planning, e.g., in a GPS-denied environment, but also to search problems such as target acquisition.

1. T. Temple and E. Frazzoli. Optimal aiming off: Stochastic path planning with one-dimensional features. In Proc. American Control Conf., 2011. To appear.

Human Supervisory Control Research (Cummings, Bertuccelli): With the increased use of multiple sensors onboard Unmanned Aerial Vehicles (UAVs), it is envisioned that UAV operators will become responsible for high-level mission supervision, such as information management and task planning. As a result, our recent work has focused in two main areas: the provision of an external decision support for helping operator schedule imagery search tasks, and understanding how operators can supervise multiple UAVs planning under a randomized algorithm. In the context of persistent Intelligence Surveillance and Reconnaissance (ISR) missions, operators supervising a large number of sensors can become overwhelmed with the sheer amount of information collected by the UAVs, making it difficult to optimize the information collection or direct their attention to the relevant data. Novel decision support technology that can supplement operator choices will therefore be required. Our recent work has considered an integer-programming formulation for allocating operator attention in sequential search tasks, and developed a non-preemptive scheduling algorithm for a single operator performing a search tasks in a time-constrained environment. This algorithm was then evaluated in a human-in-the-loop experiment for a search-scheduling task in a simulated mission. We have presented these experimental results in operator performance as well as operator task selection behavior in both conference and journal forums. The sensitivity of the proposed model was analyzed in the presence of uncertainty to the operator model and search times, and we showed that addressing various sources of uncertainty will be critical in providing effective decision support systems for operators. Ongoing work is considering the role of robustness in providing schedules that hedge against the uncertainty in the environment. In the context of supervision of randomized algorithms, we have developed a novel collaborative Rapidly exploring Random Tree (c-RRT) algorithm to support human path planning in complex dynamic environments. An experiment was designed to test how participants performed in four different modes of c-RRT operation and in one of two different obstacle densities. The four modes of operation varied in the level of interaction with the c-RRT planners, from none to modifying the RRT both before and after solution generation. Data obtained from the experiment was analyzed to investigate the human operator's impact on the algorithm's performance, the effect of the algorithm on the human, and the human's subjective evaluation of planning with the c-RRT. Overall, the c-RRT appeared to be the most helpful under high workload conditions, as represented by the high-density obstacle field in this experiment. However, while allowing human operators to guide the c-RRT algorithm's search by giving the algorithm sub-goals did show some benefits, such as decreased runtime in high density obstacle environments, the experiment showed that having humans constrain the algorithm's solution space by specifying sub-goals required improvements as it resulted in a lower actual and self-assessed performance, increased self-assessed workload, and increased level of frustration. To this end, when given the opportunity to elect to use the planner, 28% elected not to invoke the c-RRT. Reasons given in the debrief included that "it was faster to modify the previous solution" and "were not sure that the new solution would be better." This result is particularly noteworthy since the participants were all engineering students who arguably are more technically minded than likely operators who would not have such extensive engineering backgrounds. Further work is ongoing to determine if one or more design interventions could mitigate this problem.

1. Bertuccelli, L. F. & M.L. Cummings. "Scenario-based robust scheduling for collaborative human-UAV visual search tasks", IEEE Conference on Decision and Control, Orlando, USA, 2011.
2. Bertuccelli, L., Beckers, N. & Cummings, M. L. Developing Operator Models for UAV Search Scheduling, AIAA Guidance Navigation, and Control Conference, Toronto, Canada, Aug, 2010.
3. Bertuccelli, L., Pellegrino, N. & Cummings, M. L. Choice Modeling of Relook Tasks for UAV Search Missions, IEEE American Control Conference, Baltimore, MD, June 2010.
4. Caves, A. (2010), Human-Automation Collaborative RRT for UAV Mission Path Planning, M Eng Thesis, MIT Electrical Engineering and Computer Science, Cambridge, MA.

Supporting Task and Interruption Management in Multiple UAV Control through Graded Tactile and Peripheral Visual Notifications (Sarter, Prinet, Phillips and Terhune): During the early stages of this project, our team focused on designing an interface that supports effective attention management and timesharing. In particular, we developed and tested the effectiveness of peripheral visual and tactile guidance that helps operators decide when to switch attention to/from 9 live video feeds to ensure reliable target detection in parallel with performing other UAV-related tasks. Redundant visual-tactile cueing proved to be most effective and resulted in significantly improved target detection and overall mission performance. This past year, our focus has shifted towards examining different approaches for supporting dynamic re-planning during UAV operations. In particular, we have modified our UAV simulation environment to include three re-planning approaches: 1) manual, 2) collaborative, and 3) fully automated. In each case, the operators are informed by means of a salient cue when the need for re-planning emerges (e.g., to add a target or avoid a new no-fly zone). In the manual condition, they will be required to develop, explore, and select re-routing options on their own. In the collaborative condition, the automation will suggest three preferable UAV flight paths that score high on three mission criteria (schedule, safety, coverage). These preferred options will be shown on the map, and resulting mission criteria scores are indicated below. The operator examines and compares these options and then chooses/activates one of them. In the fully automated condition, the re-planning aid develops and executes a preferred new UAV path. The operator is informed about the automation choice and action and can intervene/override if necessary (management-by-exception). We have created a re-planning interface that allows the user to create and compare re-routes as quickly as possible, given the need to perform other tasks (e.g. monitoring live video feeds) that may coincide and compete for attention. This was achieved, in part, by including a direct manipulation interface where the operator can click on and drag the flight path across the screen. The effects of changing the flight path are immediately reflected in the mission criteria scores to help with comparing the desirability of each path. If the operator is not able to attend to a required re-planning task right away, it migrates to a log and can be reviewed and completed later. We plan to run an experiment this summer (UM IRB approval has been received) to evaluate the three re-planning options. Our expectation is that the collaborative condition will result in the best overall performance across mission tasks, and that it will be preferred by participants because it lowers their workload yet still leaves them in control of the re-planning process.

Flapping Wing Vehicle Dynamics and Analysis (Girard, Orlowski): The first order equations of motion for a flapping wing micro air vehicle are derived from the multi-body equations of motion [1]. The first order equations of motion are approximated using two techniques: averaging and 'quarter-cycle' averaging. Averaging does not necessarily apply and the predicted results are poor. 'Quarter-cycle' averaging presents a vast improvement of local averaging and results in an average error of around 5% [2]. The stability derivatives for a flapping wing micro air vehicle in the vicinity of a hover condition are obtained using local averaging and perturbed flight dynamics and aerodynamics models [3]. The resulting modal structure is qualitatively consistent with independent numerical analyses and the most common vertical off and landing aircraft structure. The method also scales consistently for a range of insect models.

1. C. Orlowski and A. Girard, Modeling and Simulation of Nonlinear Dynamics of Flapping Wing Micro Air Vehicles, AIAA Journal, Vol. 49, No. 5, pages 969-981.
2. C. Orlowski and A. Girard, Averaging of the Nonlinear Dynamics of Flapping Wing Micro Air Vehicles for Symmetrical Flapping, In Proceedings of the 49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 4-7 January 2011, Orlando, FL, AIAA Paper 2011-1228, 2011.
3. C. Orlowski and A. Girard, Stability Derivatives for a Flapping Wing MAV in a Hover Condition Using Local Averaging, Accepted for the 2011 American Control Conference, 29 June – 01 July 2011, San Francisco, CA, IEEE, 2011.

Air-Breathing Hypersonic Vehicles

Aeroelastic modeling of HSV and Control Surfaces (Cesnik, Skujins): The convolution-based reduced-order modeling framework for hypersonic aerodynamics has been extended to allow for multiple elastic modal oscillations through the introduction of a multi-modal correction factor. Overall, good agreement is seen for the unsteady lift, drag, and moment coefficients obtained by the ROM and computational fluid dynamics (CFD) results. ROM results have also been shown to agree well with CFD data over the range of reduced frequencies expected to be encountered in the hypersonic regime. In addition, an error estimation framework has been developed to allow for a priori estimation of both the errors expected to be incurred through the use of the ROM as well as to determine the number

of CFD training runs necessary for model construction.

1. Skujins, T. and Cesnik, C.E.S., "Reduced-Order Modeling of Hypersonic Unsteady Aerodynamics Due to Multi-Modal Oscillations", *Proceedings of the 17th AIAA International Space Planes and Hypersonics Systems and Technologies Conference*, San Francisco, California, Apr. 11-14, 2011.

Thermo-Structural Modeling (Cesnik, Falkiewicz):

A reduced-order aerothermoelastic modeling framework has been developed for the purpose of assessing the impact of aerothermoelastic effects on hypersonic vehicle flight dynamics. The proper orthogonal decomposition is used to reduce the order of the transient thermal problem. The structural dynamics equations of motion are also reduced by modal summation. To generate the boundary conditions for the thermal problem, a kriging-based aeroheating ROM developed by Crowell and McNamara at Ohio State University is employed. Third-order piston theory is currently being used to capture unsteady aerodynamic loads. The aerothermoelastic ROM methodology has been applied to a representative hypersonic vehicle elevator control surface to perform a variety of studies. Use of thermal and structural dynamic ROMs as opposed to their finite element counterparts has been shown to significantly reduce the computational cost and number of states involved in the solution. Augmentation of the structural dynamic free vibration modes with load-dependent Ritz vectors has been shown to decrease average L_∞ error by up to 38% for the cases studied. Currently, the aerothermoelastic control surface ROM is being coupled with an aeroelastic representation of a hypersonic vehicle fuselage for the purpose of full-vehicle flight dynamics simulations.

1. Falkiewicz, N.J., Cesnik, C.E.S., Crowell, A.R., and McNamara, J.J., "Reduced-Order Aerothermoelastic Framework for Hypersonic Vehicle Control Simulation," *AIAA Journal*. In Press.
2. Falkiewicz, N.J., and Cesnik, C.E.S., "Proper Orthogonal Decomposition for Reduced-Order Thermal Solution in Hypersonic Aerothermoelastic Simulations," *AIAA Journal*. Vol. 49, No. 5, May 2011.

Control-Oriented Model of the Propulsion System (Driscoll, Torrez, Dalle)

The MASIV control-oriented propulsion model was improved in several ways that were suggested by our AFRL Center collaborator, Dr. Michael Bolender. The well-known AFRL HSV hypersonic vehicle code of Bolender and Doman was modified to handle 6 DOF and is now called MASTRIM. MASIV (the Michigan-AFRL scramjet in vehicle) propulsion code was integrated into MASTRIM. Demonstrations of the code were given to AFRL, Boeing, NASA AMES and Ohio State U. Modifications were made to now include complex ethylene chemistry (in addition to hydrogen chemistry) and its real-gas properties, including dissociation losses. Our generic X-43 geometry, which was used for demonstration purposes, is being replaced with a generic X-51 geometry. The engine ram-to-scram transition was added. Performance curves were generated, which plot altitude versus Mach number, with contours of the required equivalence ratios, for a trimmed vehicle. Some operability limits were added; the performance curves are bounded by operability limits associated with flameout, excessive heating loads, poor inlet performance, and ram-scram transition. The MASIV code has been made available for distribution to those approved by M. Bolender. Two accepted journal papers in the AIAA J. of Propulsion and Power describe the validation tests of MASIV. Comparisons to high-fidelity CFD++ solutions show that the inlet ROM agrees to within 6% and the combustor ROM agrees to within 10%. An Inlet ROM solves Euler's equations rapidly using Riemann wave interaction theory for typically 20-100 shock/expansion interactions. The Combustor ROM uses pre-computed lookup tables for 3-D mixing and turbulent combustion of a fuel jet injected into an air cross flow. The tables are generated with complex ethylene or hydrogen chemistry that involves typically 20 species and 40 reactions. An Exhaust Nozzle ROM also was developed, using the same Riemann wave interaction theory as used in the inlet. The 2-D nozzle code is needed to compute the curved lower free boundary of the exhaust plume, and the recombination chemistry, both of which significantly affect the thrust.

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

GRANT NUMBER FA8650-07-2-3744

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Abstract
In its third year, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) has two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on two main issues: (i) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; and (ii) dynamic, sequential, combinatorial and/or stochastic mission planning. 2. Air-Breathing Hypersonic Vehicle (ABHV), which focuses on two main issues: (i) development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion and can be used in a 6 DOF flight dynamics simulation; and (ii) determination on appropriately modifying vehicle configuration to improve dynamic controllability without compromising performance. We expanded to include funding from the Boeing Company aimed at work in dynamics and control of flapping wing vehicles, and by adding a subcontract with Ohio State University supporting Professor Serrani on the same topic.

Status/Progress

<u>**Cooperative Control of Unmanned Air Vehicles**</u>

UAV Supervision and Control using DES (Girard, Wang): Optimization of information acquisition in distributed systems The motivation for dynamic information acquisition can be (i) to save flights in UAS for reconnaissance missions, (ii) to reduce unnecessary data collection in smart power grid systems, (iii) for security reasons, such as to prevent radar detection by enemy radars by turning them on only if necessary, and (iv) saving energy and bandwidth for sensing and communications to sensing devices. We developed efficient algorithms that are provably optimal for minimizing information acquisition under the constraint that agents are able to collect sufficient information for making correct decisions for control and fault diagnosis [J1,J2,J3,J5]. These results are being extended to the application of task assignment in reconnaissance missions of UAS. Coobservability and codiagnosability are two fundamental system-theoretic properties of partially observed distributed systems that arise in the solution of control and fault diagnosis problems, respectively. Coobservability answers the question of whether or not agents are able to collect sufficient information to make correct control decisions; codiagnosability concerns identifying trajectories that contain unobservable fault events. We have investigated these two properties [J4]. We proved that problems of coobservability are reducible to problems of codiagnosability in dynamic observations. We also developed verifiers for testing coobservability and codiagnosability for dynamic observations.

Stochastic Approximation for Optimizing Human Performance (Girard, Wang, Gong): We developed stochastic approximation that can optimize an unknown concave function when optimum solution is not unique. This technique can be used to adjust workload for human operators such that the optimum rate of correct decisions can be achieved when the workload and performance function is unknown [C1].

[J5] W. Wang, A. R. Girard "An Online Optimizing of Information Acquisition in Supervisory Control and its Application in Smart Power Grids", accepted by Automatica, 2010
[J4] W. Wang, A. R. Girard, S. Lafortune, and F. Lin, "On Codiagnosability and Coobservability with Dynamic Observations", resubmitted to IEEE Transactions on Automatic Control, 2010
[J3] W. Wang, A. R. Girard, and C. Gong, "Computing all Minimal Sensor Activation Policies", accepted by IEEE

Transactions on Automatic Control as a Technical Note, 2010
[J2] W. Wang, S. Lafortune, A. R. Girard, and F. Lin, "Optimal Sensor Activation for Diagnosing Discrete Event Systems", Automatica, July 2010
[J1] W. Wang, S. Lafortune, F. Lin, and A. R. Girard, "Minimization of Dynamic Sensor Activation in Discrete Event Systems for the Purpose of Control", IEEE Transactions on Automatic Control, Nov. 2010
[C1] C. Gong, A. R. Girard, and W. Wang, "Stochastic Approximation to Optimize the Performance of Human Operators", in Proc. 2010 American Control Conference

Heterogeneous Human Operator Team in Classification Task: Modeling and Supervisory Control using Discrete Event System (Girard, Hyun, Wang): The development of autonomous and semi-autonomous vehicles altered the human operator's role from that of pilot, directly controlling the vehicle, to that of supervisor, making higher-level decisions, interpreting sensor data, and monitoring the evolution of missions. The complementary aspects of the autonomous vehicle – human operator team encourage the use of such a team for various missions We develop Discrete Event System (DES) models of human operators in a classification task and a supervisory controller structure that positively regulates the operator behavior. Results in Proceedings of the ACC 2010.

Optimally Informative Path Planning for Dynamic Bayesian Classification (Girard, Kabamba, Hyun): An agent, consisting of an Unmanned Aerial Vehicle (UAV) carrying strapped-down sensors, is to examine a number of unidentified objects within a given search area, collect information, and utilize that information to classify the objects. The problem is challenging because the mission time is often limited, the agent is only provided with partial a priori information, and the amount of information that the sensor can measure is dependent on the relative position of the agent with respect to the object. Our technical approach is three-fold. First, we model the motion of the agent using a kinematic model with constant altitude. Second, we use a performance prediction model that gives the probability of target discrimination as a function of the range from the sensor to the object. Third, a linear classifier that utilizes Bayes' theorem diagnoses the status of the objects of interest while an information theoretic measure is used to quantify the uncertainty in classification. We pose an optimal control problem that minimizes the classification uncertainty while taking differential constraints and the time history of the agent's steering decisions as the control input. This problem is solved numerically. Results to be presented at CDC 2010.

Incremental sampling-based motion planning (Frazzoli, Karaman): In order to address the computational challenges common to many real-time planning and control problems, we have considered the class of incremental sampling- based algorithms due to the "anytime" nature of the solutions: typically, a feasible solution is found very quickly, and improvements are computed over time. We were able to show that state-of-the-art algorithms (such as the Rapidly-exploring Random Trees, RRT) almost surely converge to non-optimal solutions; new algorithms were proposed, called RRG and RRT*, which are provably asymptotically optimal, i.e., almost surely converge to an optimal solution. Perhaps surprisingly, the computational complexity of these new algorithms is shown to be essentially the same as that of the baseline RRT. Interestingly, the analysis of the new algorithms hinges on novel connections between sampling-based motion planning algorithms and the theory of random geometric graphs [1]. In addition, RRG is at the core of a new computational framework, enabling the efficient (i.e., polynomial time) incremental computation of mission plans subject to complex logic and temporal constraints. This can be accomplished by combining state-of-the-art motion- planning algorithms in robotics with a general class of formal language (e.g., μ-calculus) so far ignored in the context of mission specification languages [2]. The work on RRT* was recognized with the Best Open Source Code award at the 2010 Robotics: Science and Systems conference.

1. S. Karaman and E. Frazzoli, "Incremental Sampling-based Optimal Motion Planning," in Robotics: Science and Systems, 2010. Extended version submitted to Int. Journal of Robotics Research, 2010.
2. S. Karaman and E. Frazzoli, "Optimal Kinodynamic Motion Planning using Incremental Sampling-based Methods", to be presented at CDC 2010.

Cooperative Search and Service on Road Networks (Frazzoli, Temple, Savla): We consider a new class of dynamic vehicle routing problems, in which events are generated over a road network, i.e., a 1-dimensional manifold embedded in a plane. Service vehicles, e.g., UAVs are not restricted to moving on such a manifold, but can move freely in the plane. Also, events are not known to the service vehicles as they are generated, but must be first detected and localized. We devise performance bounds for such problems, and algorithms provably achieving or approximating the optimal performance, in terms of expected detection/service time [3].

3. T. Temple and E. Frazzoli, "Whittle-Indexability of the Cow Path Problem," in Proceedings of the ACC 2010.

Dynamical queues for human-in-the-loop systems (Frazzoli, Savla): A new queueing model was introduced to en- able a rigorous approach to the analysis of systems with human operators in the loop. In the proposed dynamical queue models, the server's time to process a task is based on its utilization history—recovering cognitive psychology models of human performance, in which the performance of an operator depends on its "mental arousal." We analyze the stability and achievable throughput of such queues, under deterministic and stochastic arrivals, and propose an task release control policy that achieves the maximal stabilizable throughput [4,5]. Experimental results confirm the efficacy of the proposed control law in reducing service delays and error rates.

4. K. Savla and E. Frazzoli, "Maximally Stabilizing Admission Control Policy for a Dynamical Queue," in Proceedings of the ACC 2010.
5. K. Savla and E. Frazzoli, "Maximally Stabilizing Task Release Control Policy for a Dynamical Queue," in IEEE Transactions on Automatic Control, to appear, 2010.

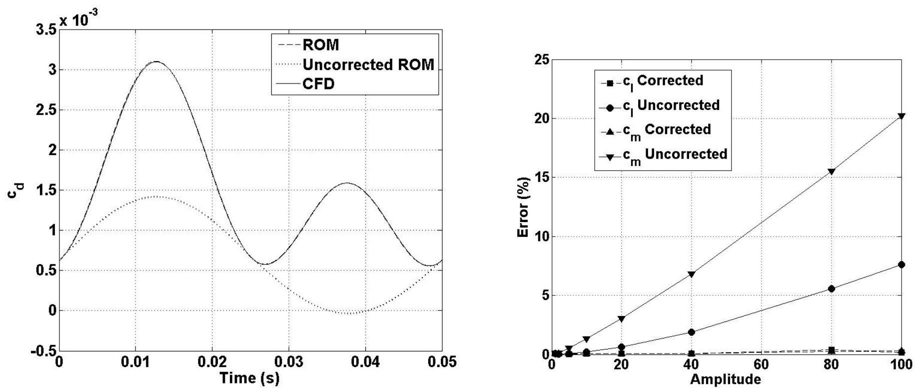
Human Supervisory Control Research (Cummings, Bertuccelli): Our most recent research efforts have built upon our earlier push on attention of operator allocation in sequential search tasks in simulated UAV environments. Our earlier experiments have demonstrated the importance of understanding operator efficiency at performing search tasks, while at the same time performing resource allocation on a team of UAVs in an environment consisting of homogeneously-scored tasks: our experimental results showed that operators improved their accuracy and decreased their search times with the help of a decision support system that alerted them when they had spent too much time searching for a particular target. Our current work is specifically tailored at understanding just how efficient human operators are at scheduling a group of sequential, but heterogeneous (different priorities), search tasks with time restrictions (e.g., tasks become available in the future). We are also interested in understanding the role of additional sources of information (in the form of a task preview) in overall operator search effectiveness, as is likely to be present in ongoing and future wide area airborne sensing programs like Gorgon Stare. Our preliminary experimental results with our novel testbed indicate that human operators are as efficient as a supportive algorithm at scheduling the search tasks. Preview capabilities appear to possibly be a distraction, but experimental results are not yet complete. An important aspect of the data that will be collected from our experiment is that it will be possible to characterize operator decision strategies (when operators choose high/medium/low value tasks vs choosing shorter duration tasks), as well as precisely understand just how effective human operators are at scheduling search tasks in time-pressure environments. This year also saw the synergistic interaction of multiple team members. In June 2010, HAL hosted a 3-week visit of Baro Hyun from Michigan to work on the measurement of UAV operator workload with the use of our eye tracker. Luca and Ketan organized and co-chaired an invited session on "Human In the Loop Control Systems" at the American Control Conference in Baltimore. Attendees included Boston University, Princeton University, University of Michigan, University of California (Santa Barbara), and MIT.

Supporting Task and Interruption Management in Multiple UAV Control through Graded Tactile and Peripheral Visual Notifications (Sarter): During the past year, the University of Michigan THInC laboratory has focused on the design of an interface that is intended to support UAV operators in re-planning and refining a mission in parallel with performing other tasks, such as monitoring the live video feed from up to 10 UAVs. In particular, we developed a human-machine interface that is distributed across three large display screens: 1) the first one includes a top-down map of the area to be surveyed and overall current mission health/status information, 2) the second relays the video/sensor data from each of 10 UAVs, and 3) the third screen supports mission replanning and displays predictions of the effects on health/status of the mission if a plan is activated. On the centrally located screen, a "configural" or "object" display is used to enable operators to assess overall mission health at a glance. This display combines four dimensions of mission status/health into a geometric figure that is symmetric as long as there are no problems with the execution of the plan or the state of resources. Once a problem is detected, the operator can use re-planning tools on the left screen where the configural display is replicated and shows how execution of the revised plan will affect mission health. This allows for iterative refinements of the plan before its implementation. It is expected that the configural display, in combination with the peripheral visual and tactile attention guidance that was developed during the first year of this effort, will allow operators to maintain awareness of higher-level mission performance with minimal cognitive effort and thus support timesharing between their monitoring and (re)planning tasks. This hypothesis will be tested empirically in a simulation study in our laboratory over the course of late Summer and early Fall.

Flapping Wing Vehicle Dynamics and Analysis (Girard, Orlowski): The flight dynamics of flapping wing micro-air vehicles were investigated through the use of multi-body equations of motion. The FWMAV is modeled as a system of three (or five) rigid bodies with three degrees of freedom for each of the wings. Simulation efforts show that the mass of the wings produces a non-negligible difference in the orientation and position of the central body of the vehicle. Additionally, the choice of different quasi-steady aerodynamic models results in a qualitative dynamic similarity. A quantitative difference exists due to the different assumptions used to obtain each of the aerodynamic models. Approximation methods focus on maintaining the inertial effects of the wing on the central body. Initial averaging efforts produce inaccurate results; when the effects are considered over the entire flapping cycle. Local averaging over quarter-cycles produces a more accurate approximation that will enable stability and control analyses that include the inertial effects of the wings on the central body. Results in AIAA Journal, to appear, 2010.

<u>Air-Breathing Hypersonic Vehicles</u>

Aeroelastic modeling of HSV and Control Surfaces (Cesnik, Skujins): The research has addressed the general modeling approach for arbitrary-shape hypersonic lifting surfaces. This work focuses on using convolution of modal step responses to construct a reduced-order model for these loads. In order to allow the model to be valid over a wide range of modal input amplitudes and flight conditions, a nonlinear correction factor is introduced. Not limited to a specific geometry, the correction factor methodology is general enough to be applied to many different two and three-dimensional vehicle configurations. Good correlation is seen between results obtained from the reduced-order model and direct computational fluid dynamics results.



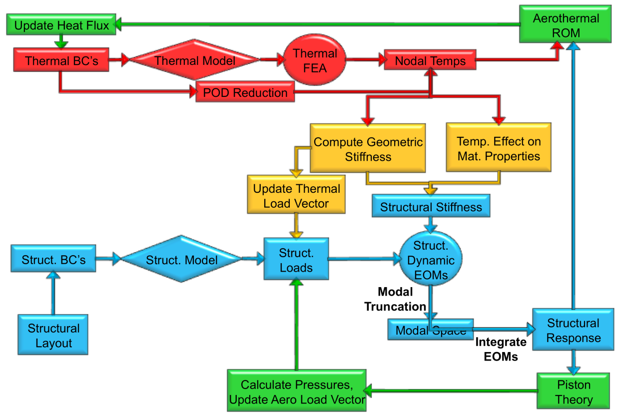
Comparison between reduced-order modeling (ROM)/convolution, with and without the newly developed correction factor, and the reference CFD results for 2D airfoils at M=8, 80,000 ft.

Publications:

6. Skujins, T., Cesnik, C.E.S, Oppenheimer, M.W., and Doman, D.B., "Canard-Elevon Interactions on a Hypersonic Vehicle," Journal of Spacecraft and Rockets, Vol. 47, No. 1, Jan-Feb 2010.
7. Skujins, T. and Cesnik, C.E.S., "Reduced-Order Modeling of Hypersonic Vehicle Unsteady Aerodynamics "Proceedings of the AIAA Atmospheric Flight Mechanics Conference, Toronto, Canada, Aug. 2-5, 2010.

Thermo-Structural Modeling (Cesnik, Falkiewicz): The aerothermoelastic framework with reduced-order aerothermal, heat transfer, and structural dynamic models have been integrated with aeroheating reduced-order formulation developed at OSU. Proper-orthogonal decomposition was used for the thermal problem. Fixed-temperature mode shapes were used for the structural dynamics part, and temperature effects in the material properties and in the form of thermal stresses are taking into account throughout the analysis. The aeroheating ROM is created using kriging on the deformed structural configuration. The approximation captures well the CFD results and provides the thermal boundary conditions for the thermoelastic problem. Still with a simplified aerodynamic (piston theory), the framework was demonstrated in a representative hypersonic vehicle control surface. The error between the reduced-order models is characterized by comparison with high fidelity models. The effect of aerothermoelasticity on total lift and drag is studied and is found to result in up to 8% change in lift and 21% change in drag with respect to a rigid control surface for the different trajectories considered. An iterative routine is used to determine the necessary angle of attack needed to match the lift of the deformed control surface to that of a rigid one at successive time instants. Application of the routine to different cruise trajectories shows a maximum departure

from the initial angle of attack of 7%. vehicle control surface as this structure is believed to have potentially the greatest impact on the dynamics of the vehicle.



Aerothermoelastic framework to be integrated into 3D hypersonic vehicle simulation

Publications:

1. Falkiewicz, N.J. and Cesnik, C.E.S., "Proper Orthogonal Decomposition for Reduced-Order Thermal Solution in Hypersonic Aerothermoelastic Simulations," *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Orlando, Florida, April 12-15, 2010.
2. Falkiewicz, N.J., Cesnik, C.E.S., Crowell, A.R., and McNamara, J.J., "Reduced Order Aerothermoelastic Simulation of a Hypersonic Vehicle Control Surface for Control System Design and Simulation," Proceedings of the AIAA Atmospheric Flight Mechanics Conference, Aug 2010. (also, submitted to AIAA J., July 2010)

Control-Oriented Model of the Propulsion System (Driscoll, Torrez, Dalle)

During the last year the MASIV control-oriented propulsion model was completed (Version 1.0) and was integrated into the AFRL HSV hypersonic vehicle code of Bolender and Doman. MASIV (the Michigan-AFRL scramjet in vehicle) propulsion code is a logical improvement to the original Doman-Bolender AFRL propulsion model; MASIV now includes complex chemistry of hydrogen or ethylene fuel, gas dissociation and recombination, and multiple inlet shock interactions. It is embedded into the AFRL HSV code and it computes thrust and moments in 1 second on a standard PC. To trim the vehicle as many as 1000 iterations are needed, which currently takes 17 minutes. MASIV 1.0 has been made available for distribution (to those approved by M. Bolender). Two accepted journal papers in the AIAA J. of Propulsion and Power describe the validation tests of MASIV. Comparisons to high-fidelity CFD++ solutions show that the inlet ROM agrees to within 6% and the combustor ROM agrees to within 10% near the design point. The current effort is to (a) integrate the propulsion ROM into the new 6 DOF flexible vehicle ROM of Cesnik, (b) to add ram-to-scram transition and (c) compute flight dynamics, transfer function poles and zeros, and sensitivity coefficients. These are planned for completion this fall.

The MASIV propulsion ROM consists of three components. An Inlet ROM solves Euler's equations rapidly using Riemann wave interaction theory for typically 20-100 shock/expansion interactions. The Combustor ROM uses pre-computed lookup tables for 3-D mixing and turbulent combustion of a fuel jet injected into an air cross flow. The tables are generated with complex ethylene or hydrogen chemistry that involves typically 20 species and 40 reactions. Experimentally determined scaling relations provide formulas for the 3-D fuel mass fractions and turbulence levels for a jet in a cross flow; these formulas are integrated to collapse the 3-D mixing and combustion into a 1-D relation for the heat addition due to combustion, as a function of the streamwise direction (x). A series of 1-D ODEs are rapidly solved which represent the conservation equations. A 2-D Exhaust Nozzle ROM also was developed, using the same Riemann wave interaction theory as used in the inlet. The 2-D nozzle code is needed to compute the curved lower free boundary of the exhaust plume, and the recombination chemistry, both of which significantly affect the thrust. The nozzle ROM has been validated against CFD++ solutions with full chemistry.

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

GRANT NUMBER FA8650-07-2-3744

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Abstract
In its second year, the Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX) has two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV), which focuses on two main issues: (i) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; and (ii) dynamic, sequential, combinatorial and/or stochastic mission planning. 2. Air-Breathing Hypersonic Vehicle (ABHV), which focuses on two main issues: (i) development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion and can be used in a 6 DOF flight dynamics simulation; and (ii) determination on appropriately modifying vehicle configuration to improve dynamic controllability without compromising performance. We expanded to include two new faculty providing expertise in human factors related to UAV research, Nadine Sarter from the University of Michigan and Missy Cummings from the Massachusetts Institute of Technology. Partial funding for the expansion was provided by the Office of Naval Research.

Status/Progress

<u>**Cooperative Control of Unmanned Air Vehicles**</u>

UAV Supervision and Control using DES (Girard, Wang, Huyn): We have investigated dynamic observations in discrete event systems (DES) and their applications in high-level control of UAV systems. In DES, system dynamics are driven by sequences of event occurrences. Unlike static observations, in dynamic observations whether or not an occurrence of event is observable not only depends on the event and sensing capabilities but also on the system trajectories. For example, agents may turn sensors on/off to choose when to observe an event. We revisited two of the most important properties ((co)observability and (co)diagnosability) in DES for dynamic observations. (Co)observability answers the questions of whether or not agent(s) are able to collect sufficient information to make correct control decisions; whereas (co)diagnosability identifies trajectories that contain unobservable fault events.

In sensor activation problems, an event occurrence is observable to an agent only if the sensor for the event is on when the event occurs. We developed algorithms for minimizing sensor activation policy under the constraint of agents collecting sufficient information for correct control decisions. Then, we investigated a similar problem for event diagnosis, in which a tradeoff between the computational efforts and the quality of the solution is obtainable. The above algorithms are of polynomial complexity to the cardinality of all input variables. Next, we solved the problem of finding all minimal sensor activation policies for supervisory control and extended it for calculating optimum sensor activation policy for stochastic automata. Finally, we developed an algorithm for optimizing online sensor activation for supervisory control, which achieves fast online calculations without restriction of solution space. We proved that, for dynamic observations, problems of (co)observability can be transformed to problems of (co)diagnosability. Static observations fell into a special case of dynamic observations. This leverages large volumes of literature that concern event diagnosis to solve the observation problems for control, in general. We also developed an algorithm for verifying (co)diagnosability. By using our transformation method, the verifier for (co)diagnosability can be used for testing (co)observability for dynamic observations as well.

We have also developed a DES methodology for modeling tactical battlefields and are currently applying our results to realistic examples. Our results are summarized in the following publications:

1- W. Wang, S. Lafortune, F. Lin, and A. R. Girard "Minimization of Dynamic Sensor Activation in Discrete Event Systems for the Purpose of Control", Accepted, IEEE Transactions on Automatic Control, 2009
2- W. Wang, A. R. Girard, S. Lafortune, and F. Lin "The Verification of Codiagnosability in the Case of Dynamic Observations", Accepted, 2009 European Control Conference.

3- W. Wang, S. Lafortune, A. R. Girard, and F. Lin, "Dynamic Sensor Activation for Event Diagnosis", American Control Conference, Missouri, SL, June 2009.

UAVs in Adversarial Environments and Mission Planning (Girard, Faied): We consider decision makers in an extended complex enterprise, each with a different objective function and hierarchy of decision structure. We derived a state space dynamic model of an extended complex military operation that involves two opposing forces engaged in a battle. The model assumes a number of fixed targets that one force is attacking and the other is defending. The optimal solution for such a complicated dynamic game over all stages is computationally extremely difficult. We proposed an expeditious suboptimal solution where decisions are decomposed hierarchically and the task allocation is separate from cooperation decisions. Results are summarized in: M. Faied, I. Assanein, and A. Girard, "UAVs Dynamic Mission Management in Adversarial Environment" Accepted, International Journal of Aerospace Engineering, 2009. In addition, we consider a class of mission planning problems that generalizes the standard Vehicle Routing Problem (VRP) to incorporate timing constraints specified via Metric Temporal Logic (MTL). A tree search algorithm is provided to solve that VRP with MTL specifications (VRPMTL) to optimality. Current work involves dynamic local plan modifications. Results are summarized in: M. Faied, and A. Girard, "Dynamic Optimal Control of Multiple Depot Vehicle Routing Problem with Metric Temporal Logic," American Control Conference, Missouri, June 2009.

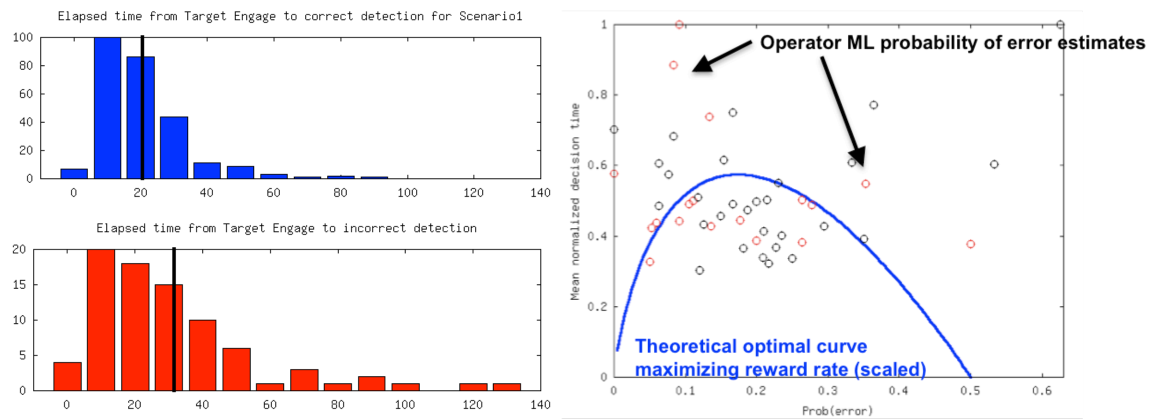
Planning algorithms for dynamical systems with complex specifications (Frazzoli, Seraman): A major challenge for autonomous systems is that the objectives and constraints of typical missions are often described by fairly complex, logical, temporal, and rule-based conditions. Examples range from the rules of the road to Rules Of Engagement (ROE) in a military setting. Planning and control systems must not only ensure the physical safety of the robot (e.g., avoiding collisions), but also that the robot abides by the relevant rules. Such constraints cannot be handled by standard robotic motion planning algorithms. Our most recent work in this context is aimed at addressing the completeness and computational challenges of existing methods for general dynamical systems subject to temporal/logic constraints. Specifically, instead of relying on a fixed abstraction of the underlying dynamical system, we incrementally construct a discrete transition system representing a sample of the feasible trajectories for the system. This is done by extending sampling-based motion planning algorithms from the literature (such as RRTs or PRMs) to allow for the construction of dense transition systems, allowing cycles (and hence infinite-length trajectories, necessary to satisfy general ω-regular specifications). At each iteration, incremental model checking is performed on the current transition system, establishing whether it is rich enough to contain behaviors satisfying the specifications. As a general formal language, we focused on deterministic π-calculus, a temporal logic that is known to (i) admit efficient model-checking algorithms, and (ii) be strictly more expressive than other temporal logics used in the literature. The proposed algorithms are shown to be sound and probabilistically complete; the complexity per iteration is polynomial in the size of the specification.

Humans-in-the-loop queueing systems (Frazzoli, Temple, Savla): During the first year of the project, in collaboration with Prof. Cummings, we established quantitative relationships linking the time a human operator needs to complete a task with his/her workload. This gives rise to a mathematical model of a queueing system with load-dependent service time. We analyzed the stability of the resultant dynamical queue, where the queue is said to be stable if the number of outstanding tasks for the operator do not grow unbounded. We characterized the stability criteria for such queues in terms of the maximum arrival rate for which there exists an admission control policy to guarantee stability of the queue. We proposed a simple threshold based admission control policy that assigns a task to the operator only if the utilization factor of the operator is less than or equal to a critical value, and prove that this policy is indeed an optimal stabilizing admission control policy. Moreover, we showed that, in the absence of an admission control policy, the dynamic queue is stable conditional on initial conditions. This is in stark contrast to the setting of a conventional queue, which has no server dynamics, where it is known that an admission control policy is not required to ensure stability of the queue. This finding has a direct implication for support system design for human operators in the context of humans-in-the-loop systems. Additionally, our result on the stability criteria for dynamical queues serves as a useful guideline for determining the number of human operators required to sustain specified workloads in dynamic missions.

Indexability and strong heuristic design for on-line decision making (Frazzoli, Temple, Savla): Motivated by a number of on-line decision making problems arising in UAV routing, and target analysis and classification by human operators, we considered an abstract problem, often called the Cow Path Problem (CPP), which we believe well encompasses the main challenges in the motivating problems. Roughly speaking, the CPP is an on-line search

problem in which n short-sighted cows search for a reward (say, a patch of clover) on k > n paths which diverge from a single origin and never cross. The cows would like to find the reward while minimizing the time spent searching. This clearly models search problems for UAVs, but also is a good model for human operators making decision on which video streams to monitor in order to find/detect targets. The CPP is typically treated with competitive analysis: we proposed an alternative approach, posing the problem as a Markov Decision Process (MDP). Our major technical contribution was to prove that when posed as an MDP, a slightly relaxed version of the problem is Whittle-indexable; we also present the corresponding index heuristic. This result also provides an insight: theoretical properties that have been empirically vetted (such as the Whittle index) are a means to bridge the gap between theory and practice in on-line decision-making problems.

Human Supervisory Control Research (Cummings, Bertuccelli): As part of the C2UAV effort, the Humans and Automation Laboratory (HAL) has been investigating the modeling aspects of visual search in the control of multiple UAVs, specifically investigating if search time is correlated with performance and if so, can an automated system prompt a user to move to another image after some period of time and/or revisit a target? One of the key results in our research thus far has been that operator error rates (in terms of target detection) are not significantly impacted by operator utilization: this has an implication that operator "business" may only significantly affect search time, and not errors directly. Another key result has been the identification that in a visual search signal detection task (target found or not found) operators' performance deviates significantly from the optimal performance of a two-alternative choice task predicted by the literature. Ongoing work is investigating the role of relooks (requeuing a visual task) as a possible method to improve overall search task performance. By allowing for a relook, ongoing work is investigating whether providing the operator with the additional flexibility to temporarily put off a target that is difficult to search and/or move on to more pressing tasks can present a benefit in terms of overall mission performance.



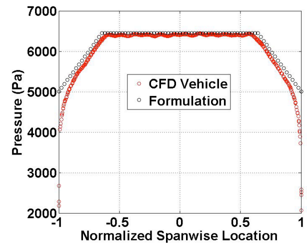
Search time histograms for successful (top) and unsuccessful (bottom) searches and mean decision time and error rate (ML denotes maximum likelihood estimate of error rate)

Supporting Task and Interruption Management in Multiple UAV Control through Graded Tactile and Peripheral Visual Notifications (Sarter): During the past year, we have focused primarily on the development of graded multimodal cueing techniques in support of attention management in multiple UAV control. To this end, we first created a multi-U/MAV control simulation in our laboratory which will allow us to run controlled experiments related to enhancing both attention management and decision making (the second main thrust of our work) in UAV operators. This testbed resembles, in terms of interface and functionality, the Vigilant Spirit simulation. It provides, on one monitor, a top-down view of the area of interest, the flight paths of 9 MAVs, and status information for each vehicle (e.g., system and fuel status, ETA at next target). On a second, adjacent monitor, controllers are presented with video feeds from the cameras of all nine vehicles. To support them in managing their attentional resources while performing competing tasks (monitoring the progress and health of the MAVs, detecting the presence of targets in the imagery, and responding to information requests via a chat box), candidate vibrotactile and peripheral visual notifications have been designed and implemented. The effectiveness of these cues will be examined and compared to a baseline (no attention guidance, as in current operations) condition in the context of the above simulation. We expect to conduct this study in the next two months and will present our findings at the review in September. In parallel, we have continued our review of the literature on UAV controller decision-making and have

explored the affordances of the Foxhunt simulation in preparation for our planned work on decision aiding and decision support.

Air-Breathing Hypersonic Vehicles

Aeroelastic modeling of HSV and Control Surfaces (Cesnik, Skujins): During this second year, research focused on the extension of the two-dimensional oblique shock/expansion fan formulation to three dimensions. The basis of the formulation is to determine the regions on the surface where the edge effects are significant. Combining the Mach angle along the edges with the conical flow equations (Taylor-Maccoll equations) we were able to evaluate the pressure distribution over the finite surface very closely with what a CFD solution predicts. Future work will include viscous effects in multi-facet surfaces.

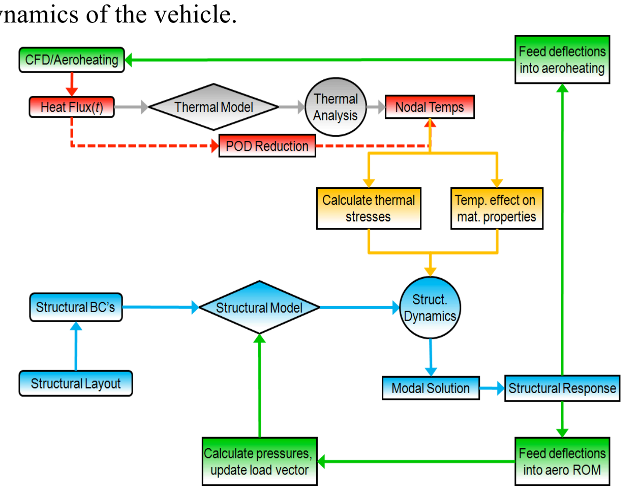


(a) Results: M=8, α=β=0°

3-D Pressure Formulation

Publications: Frendreis, S., Skujins, T., Cesnik, C.E.S, Bolender, M.A., and Doman, D.B., "Six-Degree-of-Freedom Simulation of Hypersonic Vehicles," Proceedings of the AIAA Atmospheric Flight Mechanics Conference, Chicago, IL, Aug. 10-13, 2009. AIAA-2009-5601.

Thermo-Structural Modeling (Cesnik, Falkiewicz): Significant progress has been achieved in the development of an integrated, reduced-order thermo-elastic modeling framework for fundamental characterization of the impact of aerodynamic heating on the structural dynamics and controllability of hypersonic vehicle's structures. The emphasis in this methodology was to obtain structural modes and frequencies as a function of the thermal boundary conditions and initial conditions without having to solve the full-order thermo-elastic problem at every time step. Proper Orthogonal Decomposition (POD) is used for solution of the transient heat transfer problem. A structural dynamics solution procedure was conceived in which thermal effects (temperature-dependent Young's modulus and thermal stresses) are coupled to the structural dynamics through the discrete form of the Ritz method. The methodology has been exercised in a representative hypersonic vehicle control surface as this structure is believed to have potentially the greatest impact on the dynamics of the vehicle.



Role of POD on the overall thermo-elastic problem

Publications: Falkiewicz, N., and Cesnik, C.E.S., "Reduced-Order Thermo-Elastic Modeling of Hypersonic Vehicles," Proceedings of the AIAA Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA May 4-7, 2009.
Falkiewicz, N., Cesnik, C.E.S., Bolender, M.A., and Doman, D.B., "Reduced-Order Thermoelastic Formulation of a Hypersonic Vehicle Control Surface for Control-Oriented Analysis," Proceedings of the AIAA Guidance, Navigation, and Control Conference, Chicago, IL, Aug. 10-13, 2009. AIAA-2009-6284.

Control-Oriented Model of the Propulsion System (Driscoll, Torrez, Dalle)
A new scramjet engine model, called MASIV, has been developed specifically for control-oriented applications. To speed up the calculations it includes reduced-order modeling that takes high-fidelity results from 3-D CFD and experiments and converts them to general non-dimensional scaling laws and lookup tables. It has been added to a larger control-oriented model of the hypersonic vehicle - the AFRL code (HSV) of Doman, Bolender and Oppenheimer which computes the vehicle trim conditions, stability, and dynamics. New aspects of the MASIV propulsion submodel are the following. (a) Real-gas effects are included to handle finite rate ethylene or hydrogen chemistry, gas dissociation and recombination. (b) A new fuel-air mixing/combustion model is based on general scaling laws for jets in cross-flows. It is combined with a modern assumed-PDF turbulent combustion approach. (c) A new isolator analysis simulates combustor-isolator interactions during the ram-scram transition. (d) A supersonic inlet analysis handles shock-shock and shock-expansion interactions using the exact equations, but for simplicity the expansions are discretized into a finite number of waves. It has simple formulas to rapidly correct for inlet boundary layer displacement thickness and rounded leading edges. Assessment efforts are conducted to determine the accuracy and robustness of this reduced-order approach. Four papers summarize results to date; they are:

1. A Scramjet Engine Model Including Effects of Precombustion Shocks and Dissociation, SM Torrez, NA Scholten, D J Micka, JF Driscoll, MA Bolender, DB Doman, MW Oppenheimer, AIAA Paper 2008-4619.
2. Effects of Improved Propulsion Modeling on the Flight Dynamics of Hypersonic Vehicles SM Torrez, JF Driscoll, MA Bolender, MW Oppenheimer, DB Doman, AIAA Paper 2008-6386
3. Flight Dynamics of Hypersonic Vehicles, Effects of Improved Propulsion Modeling, SM Torrez, JF Driscoll, D Dalle, M Fotia, MA Bolender, DB Doman, AIAA Paper 2009-6152.
4. Scramjet Engine Model MASIV: Role of Finite-Rate Chemistry and Combustor-Isolator Interactions, SM Torrez, JF Driscoll, D Dalle, DJ Micka, MA Bolender, DB Doman, AIAA Paper 2009- 4939.

The MASIV propulsion submodel to the AFRL HSV vehicle code has undergone preliminary validation by comparing results to the CFD++ high fidelity computations for the inlet and the combustor. The validity of the CFD++ code was assessed using experimental supersonic combustion data obtained on another project at Michigan. It is concluded that the MASIV code does properly account for real gas effects, dissociation, fuel-air mixing, and complex inlet shock interactions. The thrust predicted by the new MASIV model causes a shift in the poles and zeros of the transfer function that relates the vehicle angle of attack to the elevon settings. The short-period poles move closer to the imaginary axis. The unstable transmission zeros associated with the flight path angle are also observed to move towards the imaginary axis, and take a much more pronounced shift as compared to the short-period poles. This is attributed to a reduced lift curve slope and pitch stiffness for the high fidelity propulsion system model that stems from an change in the thrust sensitivity to angle-of-attack.

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MICHIGAN/AFRL COLLABORATIVE CENTER IN CONTROL SCIENCE (MACCCS)

GRANT NUMBER FA8650-07-2-3744

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Abstract
The mission of the Michigan/AFRL Collaborative Center in Control Science (MACCCS) is to establish, sustain and amplify an internationally recognized center of excellence in control science research and education, through interaction between the faculty and students at the participating universities, and AFRL. There are two main concentration areas: 1. Cooperative Control of Unmanned Air Vehicles (C2UAV): This concentration addresses the problem of coordinating the motion of a large number of heterogeneous mobile agents, in order to provide persistent, real-time, human-driven tactical services to operators in the field. The work focuses on two main issues: (i) supervision and control of cooperative heterogeneous systems, in the perspective of mixed-initiative operations; and (ii) dynamic, sequential, combinatorial and/or stochastic mission planning. 2. Air-Breathing Hypersonic Vehicle (ABHV): Designing effective controllers for ABHV requires reliable characterization of these vehicles' dynamics, which come from the interactions between the aerodynamics, elastic airframe, heat transfer, and propulsion system. The work focuses on two main issues: (i) development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion and can be used in a 6 DOF flight dynamics simulation; and (ii) determination on appropriately modifying vehicle configuration to improve dynamic controllability without compromising performance.

Status/Progress

Cooperative Control of Unmanned Air Vehicles

Multi-UAV Mission Planning with Linear Temporal Logic Specifications: Planning missions for a team of several UAVs in the modern battlefield is a critical and extremely demanding task. Missions involving the coordination of many possibly heterogeneous resources are typically composed of many sub-tasks which need to be completed in a given temporal order, or according to logical constraints. In order to address such class of problems, we concentrate on the so-called Vehicle Routing Problem (VRP) as an algorithmic foundation. We developed an approach enabling the formal specification of complex missions as a VRP subject to temporal and logical constraints, using a formal high-level language. Using formal methods, we are able to compute optimal plans for a large class of missions that, to our knowledge, have neither been dealt within the Mission Planning application domain nor considered in a more general VRP setting. Details are given in [Karaman et al. 2008a, 2008b, 2008c, 2008d].

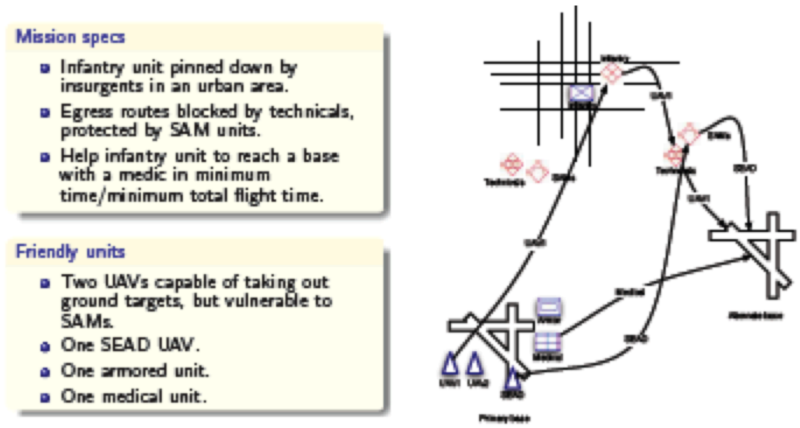

Figure 1: Example of mission planning inspired by the “Black Hawk Down” Incident.

Human-in-the-Loop Vehicle Routing Policies for Dynamic Environments: One of the prototypical missions involving Uninhabited Aerial Vehicles (UAVs), e.g., in environmental monitoring, security, or military setting, is wide-area surveillance. Low-altitude UAVs in such a mission must provide coverage of a region and investigate events of interest as they manifest themselves. UAV motion planning algorithms for such missions have been the subject of many research efforts. However, most prior work assumes that UAVs are perfectly autonomous and do not require any supervision from a human operator at any time during the mission. Even though one can foresee UAVs to have completely automated guidance and navigation modules in the near future, the role of human operators will be indispensable when the servicing of targets involves on-site decision making that require high level of cognitive capabilities provided only by a human. Also, the role of a human operator becomes critical in decision making processes where the penalty for taking a wrong decision is substantial. For instance, wrongfully identifying an unknown object in a surveillance mission can have dire consequences. Details are given in [Savla et al. 2008a, 2008b].

Cooperative Defensive Surveillance using UAVs: We present a control algorithm for a team of Unmanned Aerial Vehicles patrolling an area. The problem is formulated for a team of dynamically (turn-rate) constrained UAVs with constant velocities, to optimize a reward function by tending to areas of high interest while attending to enemy threats. A Particle Swarm Optimization (PSO) technique is used to search the control space and optimize over the control sequence. This approach guarantees feasible trajectories, without trajectory smoothing, and can be used online to calculate optimal trajectories.

Path Planning for Cooperative Information Collection: Motivated by the requirements of exploration missions, we have considered path planning for autonomous, possibly heterogeneous, agents equipped with range limited sensors. In a typical exploration problem, the decision of where to go strongly influences the quality of information received, which depends on the vantage point. This coupling of kinematics and informatics makes exploration problems particularly challenging. From this construction, properties of optimal paths can be found amongst isolated and clustered objects of interest for isotropic and non-isotropic sensors. Properties of the paths greatly rely on the inherent connection between communication and exploration, formalized through use of a Kalman filter whose covariance depends upon the range to the object. Results are detailed in [Klesh et al. 2008a, Klesh et al. 2008b].

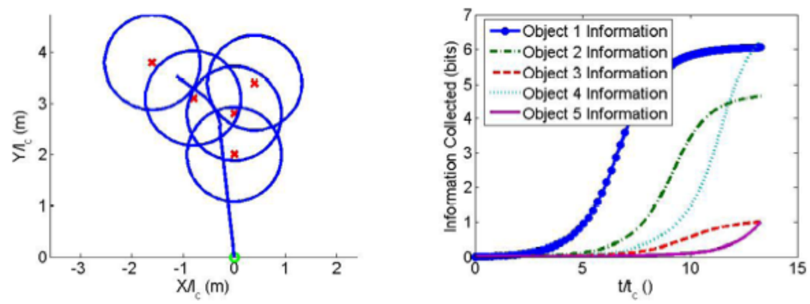

Figure 2: Time optimal paths through cluttered objects and collected information amounts.

UAVs in Adversarial Environments: We consider the modeling required to perform high-level tasks with a team of UAVs in the context of adversarial operations. Using a GUI, the operator can quickly create an environment by specifying the location of enemy vehicles and targets, friendly units, and any impassable obstacles, and issue high level commands to create a mission. Results are summarized in [Faied and Girard 2008].

Air-Breathing Hypersonic Vehicles

Aeroelastic Modeling of HSV and Control Surfaces: Research focused on the aerodynamic effects and model development for a hypersonic vehicle with canard control surfaces on the forebody and elevon control surfaces in the aftbody. The flow behind the canard was shown in certain conditions to be different than freestream flow. Specifically, a slipstream of equal pressures but unequal Mach numbers, temperatures, and other flow properties forms at the trailing edge of the canard. To study the effect of this slipstream, an analytical formulation using the oblique shock/expansion fan equations was devised to calculate the flow conditions incident on the elevon, taking the slipstream into account. To test the validity and range of applicability of this formulation, a parametric study varying the vehicle geometry and flow properties was conducted. Euler solutions obtained from computational fluid dynamics (CFD) tests were compared to the results given by the analytical formulation. The metric used in the comparisons was the elevon effectiveness ratio, which is a measure of how much the moment due to the elevon (and, therefore, vehicle control) changes when a canard is placed upwind versus the assumption that the elevon sees freestream flow. These studies are discussed in detail in [Oppenheimer et al 2008, Skujins et al 2008].

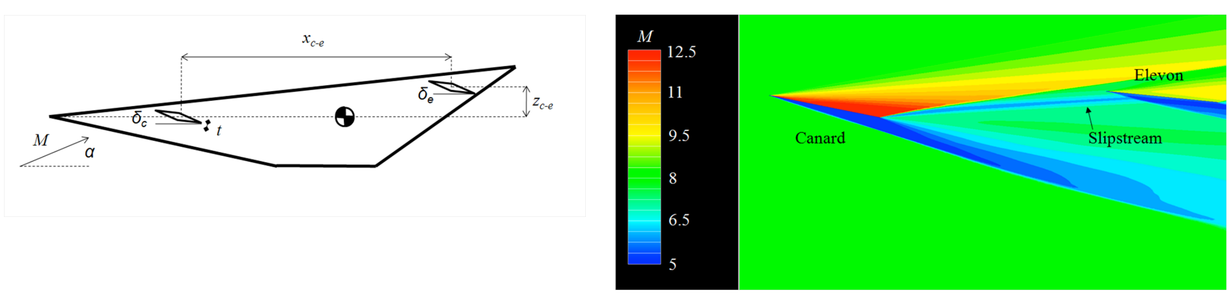

Figure 3: Hypersonic vehicle parameter diagram and Mach contour plot showing slipstream location.

Thermo-Structural Modeling: The goal of this study is to develop reduced order modeling techniques to assess the aerothermoelastic response of air-breathing hypersonic vehicles (HSVs). At hypersonic speeds, a vehicle will experience heat flux at the surface. As heat propagates through the structure, the dynamic response of the vehicle will change due to temperature dependence of material properties. Simple or reduced order models are sought in determining dynamic response as function of outside temperature and heat flux boundary conditions since a detailed finite element model is not feasible for the controls modeling and simulation. The current focus of this research is fundamental thermo-elastic modeling of an HSV control surface.

Control-Oriented Dynamic Model of the Scramjet Propulsion System of a Hypersonic Vehicle: The goals of the propulsion modeling research are the following: a) Develop a Reduced Order Model (ROM) that simulates realistic propulsion physics of a dual-mode scramjet on a timescale that is suitable for dynamics and control simulations. b) Develop a Truth Model, which is a higher-fidelity version of the current AFRL fundamental propulsion model, by adding real gas effects (dissociation, variable heat capacities), finite-rate combustion and recombination chemical kinetics, a fuel-air mixing submodel, isolator shock losses, and ram-to-scram transition. It is higher fidelity but does not provide solutions on the short time scale of the ROM. c) Obtain Efficiency Functions for engine components that are needed as look-up tables in for both the ROM and the fundamental truth model. High-fidelity CFD codes (CFD++, CFL3D) provide the inlet efficiency function in terms of a look-up table, which depends on inlet shocks, the isolator efficiency function, which depends on boundary layer separation, and 3-D fuel-air mixing efficiencies. d) More realistically simulate the dynamics of the interactions between the aerodynamics and the engine components using the ROM and truth models. The bow shock interacts with the engine inlet, causing unsteady spillage. The isolator shocks interact with the combustion. Results are summarized in [Torrez et al., 2008a, Torrez et al., 2008b].

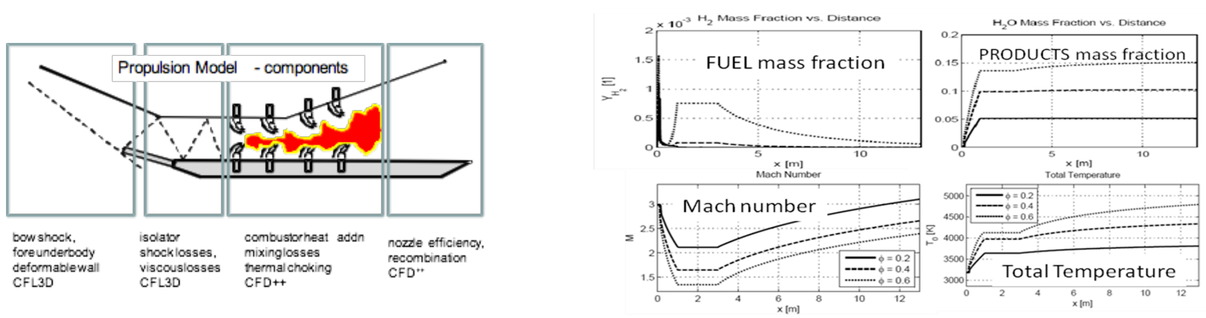

Figure 4: Some results of higher-fidelity fundamental Truth Model of the propulsion system – computed fuel and product mass fraction, Mach number and total temperature in a Dual Mode Scramjet operated at Mach 8, including dissociation losses and finite rate chemical kinetics.

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References:

See Publications

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Publications

S. Karaman and E. Frazzoli. Complex mission optimization for multiple UAVs using linear temporal logic. In American Control Conference, Seattle, WA, 2008.

S. Karaman and E. Frazzoli. Vehicle routing with linear temporal logic specifications: Applications to multi-UAV mission planning. In AIAA Conf. on Guidance, Navigation, and Control, Honolulu, HI, 2008. To appear.

S. Karaman and E. Frazzoli. Vehicle routing problem with metric temporal logic specifications. In IEEE Conf. on Decision and Control, 2008. To appear.

S. Karaman, R. Sanfelice, and E. Frazzoli. Optimal control of mixed logical dynamical systems with linear temporal logic specifications. In IEEE Conf. on Decision and Control, 2008. To appear.

K. Savla, T. Temple, and E. Frazzoli. Human-in-the-loop vehicle routing policies for dynamic environments. In IEEE Conf. on Decision and Control, 2008. To appear.

K. Savla, T. Temple, and E. Frazzoli. Efficient routing of multiple vehicles for human-supervised services in a dynamic environment. In AIAA Conf. on Guidance, Navigation, and Control, Honolulu, HI, 2008. To appear.

A.T. Klesh, A.R. Girard and P.T. Kabamba, Real-Time Path Planning for Time-Optimal Exploration. Accepted for Publication in the Proceedings of the AIAA GNC Conference 2008.

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M. Faied and A.R. Girard, Hybrid System Modeling for UAV Adversarial Operations. Accepted for Publication in the Proceedings of the ASME Dynamic Systems and Controls Conference, 2008.

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T. Skujins, C.E.S. Cesnik, M. Oppenheimer and D. Doman, Applicability of Analytical Shock/Expansion Solution to the Elevon Control Effectiveness for a 2-D Hypersonic Vehicle Configuration. 2008 Atmospheric Flight Mechanics Conference and Exhibit, AIAA, Honolulu, Hawaii.
S. Torrez, N. Scholten, D. Micka, J. Driscoll, M. Bolender, D. Doman and M. Oppenheimer, A Scramjet Engine Model Including Effects of Precombustion Shocks and Dissociation. AIAA Paper 2008-4619, 2008 Joint Propulsion Meeting.
S. Torrez, J. Driscoll, M. Bolender, D. Doman and M. Oppenheimer, Shift of the Poles and Zeros of a Hypersonic Vehicle due to Variations in the Scramjet Engine Model. 2008 Atmospheric Flight Mechanics Conference and Exhibit, AIAA, Honolulu, Hawaii.

Honors & Awards Received
AIAA Flight Dynamics and Control Graduate Student Award, Andrew T. Klesh, 2008.

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Two MACCCS graduate students and one faculty spent the summer at WPAFB as part of the summer faculty program in 2007: John Baker (UM), Torstens Skujins (UM), Anouck Girard (UM). Four MACCCS graduate students are spending the summer at WPAFB as part of the summer faculty program in 2008: Amir Matlock (UM), Sertac Karaman (MIT), Torstens Skujins (UM), and Tom Temple (MIT). In addition, frequent visits are made by MACCCS researchers to other sites (multiple visits per semester).

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New Discoveries
None.